Evaluating agricultural management from field to catchment scale

Development of a parsimonious agro-hydrological model

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Dissertation presented in partial fulfillment of the requirements for the degree of Doctor in Bioscience Engineering

September 2016

Doctoraatsproefschrift nr. 1372 aan de faculteit Bio-ingenieurswetenschappen van de KU Leuven.

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Acknowledgements

I could never have imagined finishing this PhD manuscript, and yet here it is... Looking back at the last four years, I realize this PhD research was not only the result of my own perseverance, but also due to the immense support of many around me.

First, I would like to thank my three promotors Dirk, Jan and Patrick. They all contributed to the successful realization of my PhD research, each with their own expertise and guidance along the way.

A special thanks goes to my main promotor Dirk, who still accepted me as his PhD student right when he was about to retire. I couldn't have wished for a better promotor! With his immense enthusiasm and patience, he wholeheartedly supported me over the last 4 years. He always helped me to see the bigger picture and keep the end goal within reach. Mostly, I will forever be grateful for the opportunity to learn from him being an excellent researcher, inspiring teacher and loving family man.

Next, I am also thankful for the valuable insights and suggestions of all jury members, which have really improved the manuscript that I can proudly present today.

Furthermore, I would like to thank the Research Foundation - Flanders (FWO) for funding my research, and the technical and administrative staff of the department for assisting me with all practicalities. Especially Viviane, Petra and Karlien, who were always ready to help with a smile and took time for a small chat to check on how I was doing.

Next, I greatly appreciate the contributions of my thesis students Stien, Alexis and Omar, and would like to thank Roger Cousens, Lammert Bastiaans, Berhanu, Alemtsehay, Magali, Hector, Nirman, Felix, Gebeyehu, Quan, Els, Toon, Stefaan, Eline and Tadesse for sharing their data and expertise.

Thanks also to all enthusiastic participants of the many AquaCrop trainings. Their great interest always assured me that one day my work would make a small contribution to solve 'real' world problems.

Further, I will never forget the colleagues of tower 2. They did not only help me with my research, but made sure we had fun times in the office, during coffee breaks, lunch, dinners, BBQs, lab trips and parties. I especially want to thank those who accompanied me through a large part of my PhD time and became friends along the way: Joachim, Dries, Mattias, Helena, Kristine, Nirman, Lameck, Naomi, Jennifer, Laura and Audrey. Special thanks also to Karen, Eline and Stefaan for their ‘senior’ advice on how to survive this academic adventure.

Furthermore, I am grateful to my friends for providing excellent distraction after work. Special thanks to Veerle and Tina who, speaking from experience, always knew the right things to say.

I also would like to thank my family for believing I could, and therefore I would, finalize this PhD. Your encouragement has been invaluable to me! I especially want to thank my sister and colleague Nele. The support in and outside the office really went both ways. As she finalized her own PhD, despite all the setbacks, she is my number one role model!

Last but not least I want to thank Joachim. Being a true supporter (for both me and RSCA) he stood by the sideline cheering me on for the last four years. He was there to celebrate the successes, but also to encourage me in times of doubt and stress. He kept on believing in me, even when I couldn’t believe in myself. I can never thank him enough for listening to my daily work reports, cooking healthy brain food, making me laugh with his jokes, cheering me up with funny dance moves, and just being there for me any time, any day.

Summary

Due to the increasing world population and prosperity, global food production needs a 70% increase by 2050. To achieve this taking into account the limited land and water resources, an increase in productivity needs to be accompanied by an increase in crop water productivity. Improved agricultural management is one of the key solutions for upgrading (crop) water productivity, especially in rainfed cropping systems in drought-prone regions. However, agricultural management practices are only sustainable if they are selected considering their suitability under changing environmental conditions. Also, their potential impact on regional water availability should be taken into account.

Agro-hydrological models are suitable tools to investigate the impact of several agricultural management strategies under various environmental conditions. While simple crop and hydrological models are limited with respect to the number and accuracy of the processes they incorporate, complex models have high demand for data. Due to these limitations, there is a need for new agro-hydrological models that accurately simulate both crop productivity and water availability in agricultural catchments but have low data and calibration requirements. This study aimed at developing a widely applicable, parsimonious agro-hydrological model, AquaCrop-Hydro, by linking the process-based AquaCrop crop water productivity model with a conceptual hydrological model.

First, the AquaCrop submodel to simulate the effect of agricultural management at field scale was evaluated and further improved.

AquaCrop can simulate the effect of various agricultural management practices on the soil water balance, crop canopy development, crop transpiration and crop (water) productivity of an agricultural field. Next to irrigation management, the model considers crop management, soil management, field surface management, mulches, soil fertility management and weed management.

Two of these practices were further studied in detail. First, AquaCrop's semi-quantitative simulation procedure to simulate crop response to soil fertility stress was elaborately discussed and evaluated against field experimental data of maize and wheat in Nepal, quinoa in Bolivia and tef in Ethiopia. Second, a new procedure to simulate crop production in weed-infested fields was developed and tested against field data of barley in Ethiopia and winter wheat in Australia. Evaluation of simulation results showed that AquaCrop performed well to simulate the soil water content, crop development and production under various environmental conditions and different water, soil fertility and weed infestation levels.

Furthermore, a scenario analysis demonstrated that AquaCrop enables efficient analysis of a broad range of agricultural management practices in order to develop management strategies that are tailored to the local agronomic and environmental conditions.

Subsequently, the AquaCrop model was linked to a conceptual hydrological model. The resulting AquaCrop-Hydro model was evaluated and applied to the Plankbeek catchment, an agricultural catchment in Flanders, Belgium. Comparison against historical observations showed that AquaCrop-Hydro performed well to simulate crop production and river discharge at the outlet of the catchment. Moreover, an impact analysis demonstrated AquaCrop-Hydro's ability to evaluate various agricultural management strategies for climate change adaptation with respect to their effect on crop production as well as water availability.

Finally, the strengths and limitations of AquaCrop-Hydro as compared to other agro-hydrological models was assessed. The model is widely applicable to agricultural catchments with varying characteristics. Due to its parsimonious nature it is especially useful for application in data-scarce regions, where it provides good estimates while alleviating the burden of high data and calibration requirements. Although there is room to improve model accuracy and functionality, AquaCrop-Hydro can be applied to evaluate agricultural management strategies and support sustainable water management from field to catchment scale.

Samenvatting

Door de stijgende en steeds rijkere wereldbevolking zal de wereldvoedselproductie met maar liefst 70% moeten toenemen tegen 2050. Om deze toename te verwezenlijken op een duurzame manier rekening houdend met de schaarse bodem- en waterbronnen, zal niet alleen de landbouwproductiviteit maar ook de gewas-waterproductiviteit moeten stijgen. Het verbeteren van het veldbeheer is daarvoor een veelbelovende werkwijze, zeker voor regengevoede landbouw in droge gebieden. Maar het verbeteren van veldbeheer kan enkel op een duurzame wijze als wordt rekening gehouden met de toepasbaarheid van de beheerstechnieken in een veranderend klimaat en natuurlijke omgeving. Ook de potentiële impact van de aangepaste beheerstechnieken op regionale waterbeschikbaarheid mag niet over het hoofd gezien worden.

Agro-hydrologische modellen zijn zeer handige tools om de impact van verschillende beheersstrategieën na te gaan voor verscheidene omgevingscondities. Eenvoudige gewas- en hydrologische modellen beschrijven slechts een beperkt aantal processen op een weinig nauwkeurige manier, terwijl de meer complexe modellen dan weer veel data nodig hebben. Er is dus duidelijk nood aan eenvoudige agro-hydrologische modellen die zowel de gewasproductiviteit als de waterbeschikbaarheid in landbouwgebieden nauwkeurig kunnen simuleren maar slechts een beperkte hoeveelheid data en ijking vragen. In deze studie werd daarom een breed toepasbaar en eenvoudig agro-hydrologisch model ontwikkeld, genaamd AquaCrop-Hydro, door het fysisch gebaseerde AquaCrop gewas-waterproductiviteitsmodel te koppelen aan een conceptueel hydrologisch model.

Eerst werd de AquaCrop modelcomponent om het effect van landbouwbeheer op veldschaal te simuleren geëvalueerd en verder uitgewerkt.

AquaCrop kan het effect van een brede waaier van landbouwbeheerstechnieken op de bodemwaterbalans, gewasbedekking, gewastranspiratie en gewas-(water)productiviteit van een landbouwveld simuleren. Naast irrigatiebeheer simuleert het model ook gewasbeheer, bodembeheer, veldbeheer, bodembedekkers, bodemvruchtbaarheidbeheer en onkruidbeheer.

Twee van deze beheerspraktijken werden verder uitgediept. Eerst werd AquaCrops semikwantitatieve methode voor het simuleren van de gewasrespons op bodemvruchtbaarheid uitvoerig besproken. Deze methode werd tevens geëvalueerd met behulp van experimentele data van mais- en tarwevelden in Nepal, quinoa in Bolivia en tefvelden in Ethiopië. Ten tweede werd

een nieuwe procedure ontwikkeld om gewasproductie in velden met onkruid te simuleren. Deze procedure werd getest met data van veldstudies met gerst in Ethiopië en wintertarwe in Australië. AquaCrop presteerde goed voor de simulatie van het bodemvochtgehalte, de gewasbedekking en de gewasproductie voor verscheidene productiesystemen met variërende niveaus van waterbeschikbaarheid, bodemvruchtbaarheid en onkruid.

Daarnaast toonde een scenario analyse ook aan dat met behulp van AquaCrop verschillende landbouwbeheerspraktijken efficiënt kunnen geanalyseerd worden. Op die manier wordt het mogelijk om beheersstrategieën te selecteren die zo goed mogelijk bij de lokale agronomische condities en omgevingsfactoren passen.

Vervolgens werd het AquaCrop model gekoppeld aan een conceptueel hydrologisch model. Het resulterende AquaCrop-Hydro model werd geëvalueerd en toegepast op het Plankbeek bekken in Vlaanderen, een rivierbekken dat voornamelijk bestaat uit landbouwgebied. AquaCrop-Hydro presteerde goed voor het simuleren van gewasproductie en de waterafvoer uit het rivierbekken. Een impactstudie toonde daarnaast ook aan dat het met AquaCrop-Hydro mogelijk is om verscheidene landbouwbeheersstrategieën te evalueren die inspelen op de toekomste klimaatsverandering.

Tot slot werden de sterktes en limitaties van AquaCrop-Hydro in vergelijking met andere agro-hydrologische modellen besproken. Het model is breed toepasbaar op landbouw gedomineerde stroomgebieden met verschillende eigenschappen. Door de eenvoud van het model is het uitermate geschikt voor gebruik in gebieden met beperkte databeschikbaarheid. Daar is het in staat goede schattingen te maken en vermindert het de nood aan veel data of uitgebreide ijking. Hoewel er nog ruimte voor verbetering is op vlak van modelnauwkeurigheid en functionaliteit, is het model geschikt om landbouwbeheersstrategieën te evalueren en zo bij te dragen aan duurzaam waterbeheer van veld- tot bekkenschaal.

Abbreviations and symbols

1D	One-dimensional
2D	Two-dimensional
3D	Three-dimensional
AGIV	Agentschap voor Geografische Informatie Vlaanderen (Agency for geographical information Flanders)
AI	Aridity index
B	Dry above-ground crop biomass
BF	Baseflow
BioMA	Biophysical Models Application platform
B_{ref}	Dry above-ground biomass in a non-stressed reference field
B_{rel}	Maximum relative dry above-ground biomass
B_{stress}	Dry above-ground biomass in a soil fertility stressed field
CC	Green canopy cover
CC_0	Initial green canopy cover
CC_{TOT}	Total canopy cover of crop and weed vegetation
CC_W	Crop canopy cover in presence of weeds
CC_{WF}	Crop canopy cover in absence of weeds
CC_x	Maximum green canopy cover
cdc	Canopy decline coefficient
CDF	Cumulative distribution function
cgc	Canopy growth coefficient
CMIP5	Coupled Model Intercomparison Project Phase 5
CN	Surface runoff curve number
CO_2	Carbon dioxide
DP	Deep percolation
CR	Capillary rise
CSI	Cold stress index
DI	Deficit irrigation
DOV	Databank Ondergrond Vlaanderen (Flemish subsoil database)
D_z	Drainage at soil depth z
E	Soil evaporation
EF	Nash-Sutcliffe model efficiency
ET	Evapotranspiration

ET_0	Reference evapotranspiration
FAO	Food and Agriculture Organization of the United Nations
FC	Field capacity
$f_{CDecline}$	Soil fertility stress coefficient for canopy decline
f_{CO_2}	Factor to correct wp* to atmospheric CO_2 concentration
f_{shape}	Canopy expansion factor due to weed infestation
f_{sink}	Crop sink strength determining crop performance under elevated CO_2 concentration
f_{weed}	Weed induced increase of vegetation cover
GCM	General circulation model
GDD	Growing degree days
GIS	Geographical information system
hi	Harvest index
hio	Reference harvest index
Hs	Climate change scenario with high summer impact
HSI	Heat stress index
Hw	Climate change scenario with high winter impact
I_a	Initial abstraction
IF	Interflow
IPCC	Intergovernmental Panel on Climate Change
IR	Irrigation
IWMI	International Water Management Institute
k	Flow recession constant
Kc_{Tr}	Crop transpiration coefficient
Ke	Soil evaporation coefficient
K_{ET}	Evapotranspiration coefficient
KMI	Koninklijk Meteorologisch Instituut van België (Royal meteorological institute of Belgium)
Kr	Evaporation reduction coefficient
Ks	Stress coefficient
K_{sat}	Saturated hydraulic conductivity
Ks_b	Cold stress coefficient for biomass production
Ks_{CC_x}	Soil fertility stress coefficient for maximum canopy cover
$Ks_{exp,f}$	Soil fertility stress coefficient for canopy expansion
Ks_{wp}	Soil fertility stress coefficient for wp*
L	Climate change scenario with low impact
l	Light extinction coefficient
LAI	Leaf area index
LGP	Length of the growing period
LU	Land unit

M	Climate change scenario with mean impact
M50	Mulch resulting in 50% E reduction
M95	Mulch resulting in 95% E reduction
MODEXTREME	European Community's FP7 project on MOdeling vegetation responses to EXTREMe events
NAE	Nitrogen agronomic efficiency
OF	Overland flow
P	Precipitation
p_{BF}	Fraction of deep percolation that contributes to baseflow
polmn	Minimum air temperature below which pollination starts to fail
polmx	Maximum air temperature above which pollination starts to fail
PWP	Permanent wilting point
R^2	Coefficient of determination
RC	Relative leaf cover of weeds
RCP	Representative concentration pathway
Ref	Reference field management
Restr	Restrictive soil layer at 50 cm depth
REW	Readily evaporable water
RF	Rainfed
RME	Relative model error
RMSE	Root-mean-square error
RO	Surface runoff
RRMSE	Relative root-mean-square error
RWH	Rainwater harvesting
S	Surface storage capacity
SD	Standard deviation
stbio	Minimum growing degrees required for full biomass production
SWB	Soil water balance
SWC	Soil water content
SWC_r	Soil water content in the root zone
T0	Soil fertility treatment with application of 0% of the recommended fertilizer dose
T100	Soil fertility treatment with application of 100% of the recommended fertilizer dose
T150	Soil fertility treatment with application of 150% of the recommended fertilizer dose
T50	Soil fertility treatment with application of 50% of the recommended fertilizer dose

TAW	Total available soil water
TAW−	Field management decreasing TAW
TAW+	Field management increasing TAW
tb	Base temperature below which crop development does not progress
TF	Total flow
T_{max}	Daily maximum temperature
T_{min}	Daily minimum temperature
Tr	Crop transpiration
tup	Upper temperature above which crop development no longer increases with an increase in temperature
UN	United Nations
USDA	United States Departement of Agriculture
VHM	Veralgemeend Hydrologisch Model (generalized hydrological model)
VLM	Vlaamse Landmaatschappij (Flemish land agency)
VMM	Vlaamse Milieumaatschappij (Flemish environment agency)
vol%	Volume percentage
w	WETSPRO filter parameter
W15	Weed infestation level of 15% *RC*
W30	Weed infestation level of 30% *RC*
WC	Weed cover
WETSPRO	Water Engineering Time Series PROcessing tool
wgt%	Weight percentage
wp*	Normalized biomass water productivity
WP_{ET}	ET crop water productivity
WSI	Water stress index
Y	Dry crop yield
θ	Volumetric soil water content
θ_{FC}	Volumetric soil water content at field capacity
θ_{PWP}	Volumetric soil water content at permanent wilting point
θ_{SAT}	Volumetric soil water content at saturation
τ	Drainage coefficient

Contents

Chapter 1

Introduction

1.1 More crop per drop

To feed a growing and wealthier population with changing dietary preferences, the Food and Agriculture Organization of the United Nations (FAO, 2011) predicted that the world's annual agricultural production needs to increase by 70 % between the year 2005 and 2050. Since less than 10% of the required production increase can be achieved by expansion of arable land, the majority of the increase in food production will need to be realized by productivity gains. Such increases in crop productivity are to be attained either by increasing crop yields (77%) or increasing cropping intensity (14%).

Water scarcity is a major constraint for agriculture in many areas of the world. The International Water Management Institute (IWMI) estimated that one fifth of the world population lives in regions where the available water resources can not meet the water demand (Molden, 2007). Aside from these 1.2 billion people facing physical water scarcity, another 1.6 billion people live in areas with economical water scarcity. Although sufficient water is available in those areas, the water demand can not be met due to lack of infrastructure or financial resources. Currently, water demand for food production is one of the greatest pressures on freshwater resources. About 70% of the world's fresh water is used by the agricultural sector (FAO, 2014). In some developing countries agriculture even accounts for up to 95% of the total water withdrawl. In addition, agriculture competes with the increasing demand for water to sustain the ecosystem and meet the needs for human consumption, energy production and the industrial sector (FAO, 2011).

Considering the widespread problem of water scarcity and the agricultural sector's insecure position of being a major water consumer, it is clear that availability of water will pose a serious constraint to increase crop productivity. For that reason, it will be crucial for the agricultural sector to increase not only crop yield but also crop water productivity, i.e. crop yield per unit of water consumed, in order to produce 'more crop per drop'.

1.2 Upgrading crop water productivity in rainfed cropping systems

Global statistics (FAO, 2014) show that irrigated agriculture accounts for more than 40% of global crop production on less than 20% of the world's cultivated land. In spite of the high productivity of irrigated agriculture, a shift from rainfed to irrigated cropping systems is infeasible for many water-scarce regions in the world. Consequently, rainfed agriculture dominates world food production and will continue to do so in the future (FAO, 2011). Today, rainfed agriculture covers more than 80% of the arable land and accounts for about 60% of the global crop production. This dominance of rainfed agriculture is even stronger in water-scarce regions of Sub-Saharan Africa where rainfed crops cover more than 95% of the cultivated land (FAO, 2014). In addition, more than half of the global population growth between now and 2050 is expected to occur in Africa (UN, 2015), where people still predominantly rely on rainfed crop production (FAO, 2014).

Although high yield levels are attained in rainfed cropping systems of temperate regions with reliable rainfall and productive soils, the overall productivity of rainfed agriculture is low. Rainfed cereal yields range between 0.5 and 2 t/ha, with an average of 1 t/ha in Sub-Saharan Africa. Rockström et al. (2007) report that these yields are 2 to 4 times below the achievable yield levels for major rainfed grain crops. In addition, rainfed yields are 2.7 times lower than those obtained in irrigated cropping systems (UN, 2012). Rosegrant et al. (2002) report that in developing countries cereal yield is on average 1.5 t/ha for rainfed cropping systems, which is less than half of the average irrigated cereal yield of 3.1 t/ha. Furthermore, Zwart et al. (2010) who simulated crop water productivity levels for wheat found that highest water productivity levels (up to 1.8 kg harvestable product per m^3 of water evapotranspired) are obtained in temperate regions with high precipitation, whereas values between 0.4 and 0.8 kg/m^3 are more common in rainfed systems with low precipitation. Also Liu et al. (2007) report that low water productivity levels are more often encountered for rainfed cropping systems than for irrigated cropping systems. Due to these low productivity levels in rainfed agriculture, there is huge potential for upgrading crop water productivity, especially in low-yielding small scale rainfed cropping systems in drought-prone regions (Rockström et al., 2007; Molden et al., 2010).

Crop water productivity can be improved by developing drought-tolerant, disease-resistant or high-yielding crop varieties either via genetic engineering or by traditional breeding (Passioura, 2006; Bennett, 2003). However, improved crop varieties may only increase crop water productivity when cultivated under good agronomic conditions that are rarely encountered in farmers' fields.

Moreover, developing improved crop varieties is a time-consuming process while the need for improving agricultural productivity is urgent. Furthermore, controversy regarding potential harmful effects of genetically modified crops hinders widespread adoption. Aside from the use of improved crops, also improved agronomy can upgrade crop water productivity. There is a wide variety of agricultural management practices available that either improve yield by reducing yield-limiting factors such as nutrient deficiencies or soil salinity, or that optimize the use of the available water water resources (Passioura, 2006; Ali and Talukder, 2008).

Optimizing the use of available rainfall is crucial for rainfed agriculture. By analysing water balances of farmers' fields in rainfed tropical cropping systems (Figure 1.1), Rockström et al. (2003) found that only a small fraction of rainfall (15-30%) contributes to crop production through crop transpiration. At least 70% of the rainfall is lost trough unproductive water losses by soil evaporation (30-50%), percolation to the groundwater (10-30%) and surface runoff (10-25%). Furthermore, rainfed agriculture is subjected to the intermittent and unpredictable character of rainfall. This is especially true for rainfed cropping systems in semi-arid and dry sub-humid areas, where crop production is restricted more by variable rainfall, dry spells and droughts than by low total rainfall amounts (Rockström et al., 2007; Wani et al., 2008). As such, there is great potential to increase crop water productivity in rainfed cropping systems by agricultural management practices that reduce unproductive water losses on the one hand, and deal with rainfall variability on the other hand.

Several studies have demonstrated the potential of various management strategies to increase crop yield and crop water productivity. Pretty and Hine (2001), who analysed 90 development projects on sustainable agriculture, concluded that intensification of a cropping system and optimizing the use of locally available natural resources can increase rainfed crop yields by 50% to 100% (with cases up to 700% yield increase). Also efficient pest management shows great potential, since Oerke (2006) found that global crop losses due to pests, including weeds, animal pests, pathogens and virusses, vary between 50% and 80% if no pest control practices are applied. Furthermore, with conservation agriculture, that focuses on minimal soil disturbance by no-inversion tillage, yield increases between 20 and 120% were obtained in East Africa (Wani et al., 2008). Integrated soil and fertility management that focuses on dry spell mitigation and soil fertility can potentially more than double yield in semi-arid rainfed farming systems while at the same time improve water productivity (Rockström and Barron, 2007). In addition, a review by Hatfield et al. (2001) reports that soil management practices could increase crop water productivity by 25-40%, while modifying soil nutrient management could increase water productivity by 15-25%.

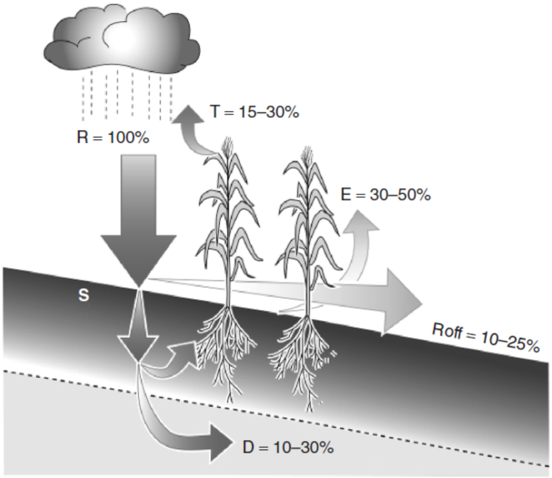


Figure 1.1: Rainfall partitioning in semi-arid tropical farming systems in Sub-Saharan Africa. S is soil moisture storage, R is rainfall, T is transpiration, E is evaporation, Roff is surface runoff and D is drainage. Source: Rockström et al. (2003)

1.3 Agricultural production in a changing environment

Despite the large untapped potential in rainfed cropping systems, increasing food production in a sustainable manner requires more than optimizing crop water productivity for each individual farmer or field. Management practices that are beneficial for one farmer might negatively affect crop productivity in a neighbouring field, and consequently impede an overall growth of agricultural productivity. Therefore, researchers such as Molden et al. (2010) and Rockström et al. (2003) stress the importance of water productivity analysis at basin scale, as upstream shifts in water partitioning might affect downstream water quality and quantity. In addition, the increase of crop productivity needs to take place in a rapidly changing world where population is growing, cities are expanding, productive land is getting scarce, several sectors and stakeholder struggle to get hold on the scarce natural resources (especially water) and society has to deal with the burden of environmental pollution and climate change.

Climate change is projected to have a substantial impact on crop production and water availability. Increased atmospheric CO_2 concentration, altered rainfall patterns, higher air temperature, increased damage due to pest, diseases and weeds, and the increased incidence of extreme weather events under future climatic conditions will affect crop growth and production, as well as availability of important resources for crop production such as water and nutrients (IPCC, 2014). Analysing more than 1090 projections, the Intergovernmental Panel on Climate Change (IPCC, 2014) found that the projected impact of climate change on crop production is highly variable, depending on the studied crop, region, adaptation scenario, emission scenario and time frame. For the near future (2030-2049), about 10% of the projections indicate a yield increase of more than 10% as compared to the late 20^{th} century, whereas another 10% of the projections show a yield loss of more than 25%. After 2050, the risks of more severe yield loss increases. Generally, crop production will be negatively affected in low-latitude countries, while the impact might be positive or negative for northern-latitude countries. In addition, climate change is projected to increase inter-annual variability of crop yields in many regions.

Also the projected effect of climate change on water availability has a high spatial variability, as changes in precipitation will not be uniform. Freshwater resources are projected to increase at high latitudes. By contrast, in dry subtropical regions, climate change is projected to reduce renewable surface water and groundwater resources significantly. This will intensify competition for water among various sectors and consequently affect regional water, energy and food security (IPCC, 2014).

Due to its effect on crop production and water availability, climate and other environmental changes will affect agricultural management, making some practices more or less effective than they are under current conditions. Also socio-economic factors might hinder adoption of certain agricultural management practices, even if they are very effective from an agronomic point of view. Molden et al. (2010) state that increasing water productivity is rarely a priority for farmers because they focus on increasing profitability or household food security. In addition, the interaction between agricultural production systems and their environment goes both ways. Changing agricultural management can also serve as a mitigation or adaptation strategy to counteract or deal with the adverse effect of environmental changes. The IPCC (2014) estimates that adaptation of agricultural management practices (including crop, irrigation and fertilizer management) could improve crop yield under future climatic conditions on average by about 15-18% of the current yield levels as compared to a business-as-usual scenario. Seen the complex interaction of agricultural production systems with their environment, a sustainable increase of crop water productivity can only be achieved using an holistic approach to evaluate agricultural management, taking into account the interactions between crop water productivity, management and the changing environmental conditions.

1.4 Tools to evaluate agricultural management

Agro-hydrological models describe agricultural practices and hydrological processes as well as their interactions in cropped land areas. Therefore, they are suitable tools to investigate the impact of several agricultural management strategies under various environmental conditions on crop water productivity at field scale as well as catchment hydrological processes (Ferrant et al., 2014).

In contrast to empirical models that use observations to describe the relation between variables, physically based models (also referred to as process-based or mechanistic models) describe the behaviour of a system based on established physical principles and laws. As a result, they have a high explanatory level and can be used to study processes transforming input into output variables. In spite of their process-based nature, also physically based models include some level of empirical generalization to fill physical knowledge gaps. This results in the need to calibrate those models against observations, although calibration requirements are lower than for empirical models. Conceptual models situate themselves in between empirical and physically based models, as they explain system behaviour based on empirical equations as well as preconceived notions on how the described system works. As both conceptual and physically based models allow representing dynamics of a system via simulation, they will be further referred to as simulation models (Wainwright and Mulligan, 2004).

Nowadays, agro-hydrological simulation models are increasingly used because they enable efficient analysis of various scenarios on a wide spatial and temporal scale. That way they can be used to analyse policies and support strategic decisions on agricultural and water management. Moreover, simulation models allow investigation of interactions between various processes in the soil-plant-water-atmosphere continuum. In addition, model based research is mostly less expensive and time-consuming than experimental research. Nevertheless, experimental data remain necessary for development, calibration and validation of the simulation models (Wainwright and Mulligan, 2004).

Most agro-hydrological simulation models are characterized either as a crop model or hydrological model, even though evapotranspiration is an important and inseparable component of the hydrological cycle.

Crop models focus on simulation of crop development and production. Typically, they operate at point scale (1D models) considering one homogeneous agricultural field. Due to the speed of crop development, crop models usually operate at a daily time step. Nowadays, more than 120 crop models are available (Rivington and Koo, 2010), each with their own strengths and weaknesses. These crop models differ with respect to the number and detail of processess that they incorporate, production situations they are dealing with (e.g. potential production versus actual production limited by various environmental factors), and their intended application domain and target audience (e.g. farmer advice tools versus research models to study resource use and efficiency)(Holzworth et al., 2015; Van Ittersum et al., 2003; Boote et al., 1996).

Hydrological models describe hydrological processes within river catchments. These catchments, also referred to as river basins or watersheds, range in size from very small (e.g. the Plankbeek catchment in Belgium covers $4.5\,\mathrm{km}^2$) to several thousands km^2 (e.g. the Amazon river basin covers $7\,050\,000\,\mathrm{km}^2$). Hydrological models represent a spatially heterogenous catchment either as a single unit (1D or dimensionless) with one set of characteristics and parameters ('lumped approach') or as a collection of several 2D or 3D units each with their own characteristics and parameters ('distributed approach'). Distributed models are further divided into 'fully distributed' models such as MIKE-SHE (Refsgaard and Storm, 1995), and 'semi-distributed' models such as SWAT (Arnold et al., 1998; Douglas-Mankin et al., 2010). The latter do not consider the spatial distribution of units within the catchment, while the former consider the exact spatial location of each unit and interactions between those units. Most hydrological models have a flexible time step for the simulation results that can be selected according to the catchment size and type of application. Flood modelling requires small time steps (hourly or even 15 minute time steps), whereas design of water storage structures can rely on simulations of water volumes at large time steps (daily, monthly or even yearly time steps).

Within the large collection of agro-hydrological simulation models, each model has its strengths but also limitations to investigate the effect of agricultural management on crop water productivity at field scale and water availability at catchment scale. Since they operate at field scale, crop models have the disadvantage that they are not able to quantify the off-site effects of agricultural management. By contrast, distributed hydrological models are able to consider both field and catchment scale. However, as these models are primarily developed to study hydrological processes they have limitations for agronomic applications. Most hydrological models implement a restricted representation of crop development and transpiration, rarely simulate crop production and water productivity explicitly, and consider only few agricultural management practices affecting crop transpiration and production. The hydrological models that do include physically based equations to estimate crop transpiration and crop production as well as the effect of agricultural management, such as SWAT (Arnold et al., 1998; Douglas-Mankin et al., 2010), MIKE SHE (Refsgaard and Storm, 1995) and APEX (Gassman et al., 2010), show relatively high computational complexity and data requirements.

Despite the increasing possibility to use remote sensing data (Boegh et al., 2004; Moulin et al., 1998), limited availability of data for input or calibration of agro-hydrological models remains a commonly encountered issue (Grayson et al., 2002; Boote et al., 1996). Also hydrological models, especially the distributed ones, suffer from large data requirements (Singh and Frevert, 2006). Conceptual models drastically reduce data requirements because of their simplicity. However, because of their conceptual nature model parameters can not be measured which again increases the need for calibration data. In the category of crop models, the AquaCrop model (Hsiao et al., 2009; Steduto et al., 2009; Raes et al., 2009; Vanuytrecht et al., 2014a) is often cited as a model with low requirements for easily obtainable input data. Comparative studies by Abi Saab et al. (2015), Castañeda-Vera et al. (2015), and Todorovic et al. (2009) note that this makes the model applicable in data-scarce regions.

It is clear that a combination of several simulation models with low data requirements is needed to obtain a parsimonious simulation tool with full functionality to evaluate the small and large scale agro-hydrological impact of agricultural management.

1.5 Research objectives

Given the limitations of existing agro-hydrological models to efficiently evaluate the potential of various agricultural management strategies to sustainably upgrade crop water productivity in an ever changing world, this PhD research intents to develop a new agro-hydrological model that meets following four criteria:

- **Criterion 1:** The model simulates crop production and water productivity at field scale, as well as hydrological processes and water availability at catchment scale
- **Criterion 2:** The model considers the effect of management and environmental changes on crop transpiration and crop (water) productivity, as well as catchment hydrology
- **Criterion 3:** The model is parsimonious, i.e. accomplishes the desired level of explanatory power with a minimum number of easily obtainable input data and parameters to be calibrated
- **Criterion 4:** The model is widely applicable, to various environmental conditions and cropping systems as well as agricultural catchments with different characteristics

The goal is to develop such a new agro-hydrological model by a combination of existing parsimonious crop and hydrological models. The process-based AquaCrop model and a conceptual hydrological model derived from the generalized conceptual model structure by Willems (2014) were selected for that purpose. To develop and evaluate this new agro-hydrological model, named AquaCrop-Hydro, following research objectives were defined (Figure 1.2):

- **RO 1:** To discuss, develop and evaluate the agricultural management calculation procedures of AquaCrop
- **RO 2:** To evaluate the use of AquaCrop as a tool to assess the effect of agricultural management strategies on crop (water) productivity at field scale
- **RO 3:** To discuss, develop and evaluate the AquaCrop-Hydro model for simulation of crop production and water availability in an agricultural catchment
- **RO 4:** To evaluate the use of AquaCrop-Hydro as a tool to assess the impact of environmental changes and agricultural management strategies on crop production and catchment water availability

1.6 Dissertation outline

This dissertation consists of two main parts that cover assessment of agricultural management at field and catchment scale (Figure 1.2). Chapter 2 to Chapter 5 deal with field scale simulations of agricultural management with AquaCrop (RO 1 and 2), whereas Chapter 6 and 7 deal with simulation of the agro-hydrological impact at catchment scale using the AquaCrop-Hydro model (RO 3 and 4).

Chapter 2 describes the AquaCrop calculations procedures to simulate the effect of agricultural management on crop development, crop production and the soil water balance. Chapter 3 and 4 elaborate on two of these agricultural management procedures that were further investigated, developed and evaluated in the framework of this PhD research. The soil fertility management procedure is discussed and evaluated in Chapter 3, whereas the development and evaluation of the weed management procedure is presented in Chapter 4. Chapter 5 demonstrates the use of AquaCrop to develop environment-specific agricultural management guidelines to upgrade crop productivity in drought-prone regions.

Chapter 6 presents the AquaCrop-Hydro model and evaluates its calculation procedures for the Plankbeek catchment, an agricultural catchment in Flanders (Belgium). In Chapter 7, AquaCrop-Hydro is applied to simulate the effect of climate change and related management adaptations on crop production and water availability in the same catchment.

Finally, conclusions and recommendations are presented in Chapter 8.

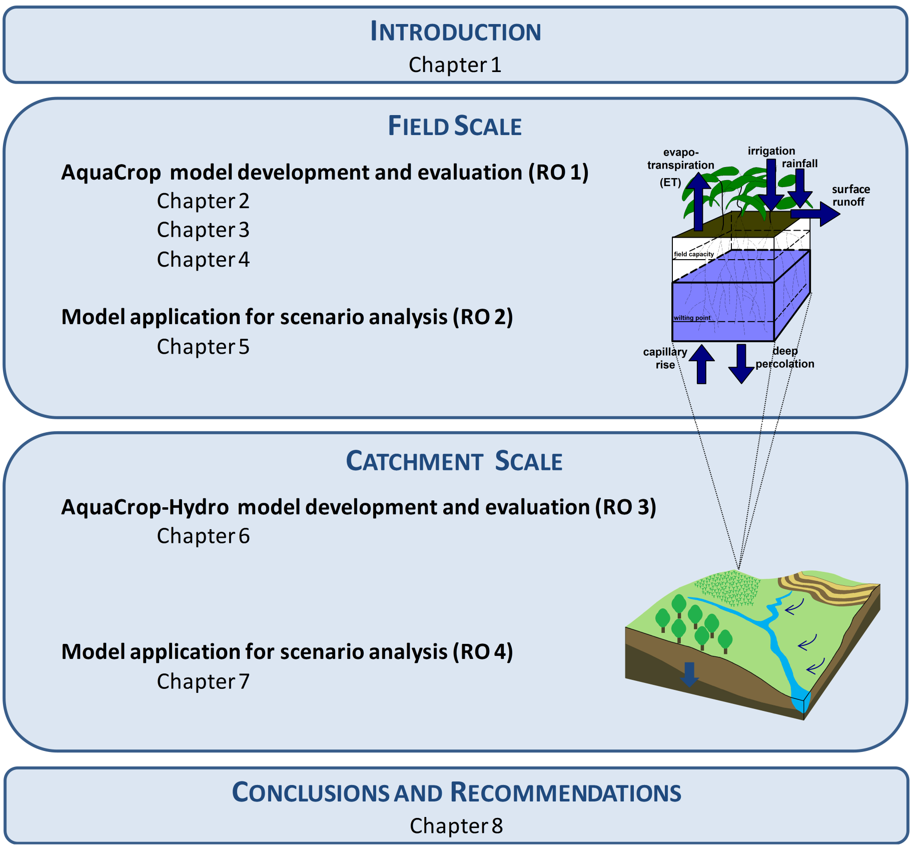


Figure 1.2: Structure of the dissertation with indication of the research objectives (RO) and corresponding chapters.

Chapter 2

The AquaCrop procedure to simulate crop response to agricultural management

2.1 Introduction

The AquaCrop crop water productivity model AquaCrop (Hsiao et al., 2009; Steduto et al., 2009; Raes et al., 2009; Vanuytrecht et al., 2014a) was developed by the Food and Agriculture Organization of the United Nations (FAO) as a tool for irrigation engineers, extension agents, agricultural policy officers and researchers that can provide quick but accurate estimates of crop production and crop water productivity under various environmental and agronomic conditions. AquaCrop simulates daily crop canopy cover, rooting depth, transpiration, dry above-ground biomass production, yield and the soil water balance in a cropped field based on user-specified inputs of environmental and agronomic conditions.

This chapter presents AquaCrop's input requirements and calculation procedures to simulate the soil water balance and crop productivity as influenced by the environmental and agronomic conditions in the cropped field. Furthermore, this chapter intents to give a complete overview of all agricultural management practices that can be simulated with AquaCrop as well as their effect on the standard calculation procedure. Also, evaluation and application of these management simulation procedures is discussed.

It should be noted that this chapter only discusses the most relevant AquaCrop calculation procedures as implemented in AquaCrop version 4.0 and 5.0. More detailed information on the algorithms and calculation procedures can be found in the AquaCrop reference manuals by Raes et al. (2012, 2015).

2.2 Input requirements

AquaCrop requires few data for input and calibration. In addition, the required input is either readily available from agricultural statistics and indigenous farmer knowledge, or can be directly measured in the field with straightforward and inexpensive methods (Vanuytrecht et al., 2014a). This makes the model easier and more widely applicable than other crop models such as CropSyst, CERES, STICS, SWAP and WOFOST, in particular for data-scarce regions (Castañeda-Vera et al., 2015; Todorovic et al., 2009; Abi Saab et al., 2015; Hunink et al., 2011).

The core input of AquaCrop is specification of the cultivated crop and its (trans)planting date. Crop characteristics are described by a set of crop parameters (Table A.2). These crop parameters describe crop growth and production under non-limiting conditions, as well as crop responses to various abiotic stresses. Parameters can be clasified as conservative and non-conservative parameters. While the former do not change with time and are valid for various environmental conditions, management practices and cultivars, the latter need calibration to match the local cultivar and cropping system. Non-conservative parameters include amongst others growing cycle length, length of different growing stages, plant density, maximum canopy cover, maximum rooting depth and crop response to soil fertility. Conservative parameters, on the other hand, include for example the water stress and temperature stress thresholds for crop development and biomass production. The AquaCrop database includes default sets of crop parameters for 14 crops (Table C.1). These include widely cultivated crops such as barley, maize, wheat and cotton (García-Vila et al., 2009; Heng et al., 2009; Andarzian et al., 2011; Abrha et al., 2012) as well as under-utilized crops such as quinoa and tef (Geerts et al., 2009a; Tsegay et al., 2012). When using these default sets, only the non-conservative parameters need to be fine-tuned to the local conditions. In total, parameter sets for more than 30 crops, calibrated for local conditions, have been presented in literature (Table C.1). These sets can be used as a starting point when calibrating conservative and non-conservative crop parameters for crops that are not yet included in the AquaCrop database.

Besides information on crop characteristics and the (trans)planting date of the selected crop, AquaCrop requires user-specified input describing the environmental and agronomic conditions of the cropped field.

Required weather data include precipitation, minimum and maximum temperature (T_{min} and T_{max}) and reference evapotranspiration (ET_0) calculated with the FAO Penman-Monteith method (Allen et al., 1998). Ideally, weather data are supplied on a daily basis, but the model can interpolate between 10-day or monthly values of T_{min}, T_{max} and ET_0 as well. In addition to these weather data, also annual average atmospheric CO_2 concentration ($[CO_2]$) is a required climate input parameter. By default, AquaCrop uses historical $[CO_2]$ measurements of the Mauna Loa Observatory in Hawaii. However, $[CO_2]$ can also be specified by the user for past or future years according to a certain CO_2 emission scenario.

Besides weather data, soil profile characteristics need to be defined. A soil profile can consist of up to 5 soil layers, each with its own set of characteristics. These include the layer thickness, saturated hydraulic conductivity ($\mathrm{K_{sat}}$) and the volumetric water content at saturation (θ_{SAT}), field capacity (θ_{FC}) and permanent wilting point (θ_{PWP}). The latter two define the total available soil water (TAW). In addition, also two soil surface parameters (surface runoff curve number (CN) and readily evaporable water (REW)), the depth of a restrictive soil layer blocking root growth (if present) and parameters defining capillary rise from the groundwater table need to be specified. Soil parameters can be specified based on field measurements, or the default values of the AquaCrop database based on the USDA soil textural class (Table A.1) can be used.

Furthermore, the groundwater, being the lower boundary condition to the soil profile, needs to be characterized with respect to its depth below the soil surface (either constant or time variable) and quality of the water. Also, information on the applied irrigation and field management practices, both during and outside the growing season, need to be specified (see Section 2.6). Finally, the model requires specification of the simulation period as well as initial conditions of soil water and salinity content.

2.3 Crop canopy development and production

Being a water-driven model, AquaCrop calculates crop production based on the amount of water transpired by the crop with a four-step process (Figure 2.1). In a first step, the crop's green crop canopy cover (CC) is simulated. The expansion of the canopy cover under non-stressed conditions from its initial value (CC_0) to reach the maximum canopy cover (CC_x) is described by a logistic function determined by the canopy growth coefficient (cgc). In the late season stage, the decline of the canopy cover due to senescence is described by means of the canopy decline coefficient (cdc). In a second step, crop transpiration (Tr) is simulated considering weather conditions (ET_0) and a crop transpiration coefficient ($\mathrm{Kc_{Tr}}$) that is proportional to the simulated canopy cover (Equation 2.1). Next, crop transpiration is converted into dry above-ground biomass production (B) by means of the normalized crop water productivity (wp^*) (Equation 2.2). In a final step, crop biomass is converted to crop yield by means of the harvest index (hi) (Equation 2.3). Crop yield per unit of water evapotranspired in the cropped field is given by the ET crop water productivity (WP_{ET}) (Equation 2.4).

Additionally, this four-step process is influenced by various abiotic factors (Section 2.5) and agricultural management practices (Section 2.6).

$$Tr_i = Ks_i \cdot Kc_{Tr_i} \cdot ET_{0_i} \tag{2.1}$$

$$B = wp^* \cdot \sum_{i=1}^{n} Ks_{b_i} \cdot \frac{Tr_i}{ET_{0_i}} \tag{2.2}$$

$$Y = hi \cdot B = f_{HI} \cdot hio \cdot B \tag{2.3}$$

$$WP_{ET} = \frac{Y}{\sum_{i=1}^{n} ET_i} \tag{2.4}$$

where Tr_i is the crop transpiration (mm/day) on day i, ET_{0_i} is the reference evapotranspiration (mm/day), Kc_{Tr_i} is the crop transpiration coefficient (-) proportional to the crop's canopy cover (CC, m^2/m^2), Ks_i is the soil water and soil salinity stress coefficient (-), Ks_{b_i} is the cold stress coefficient for biomass production (-), B is the cumulative dry above-ground biomass production (g/m^2), wp* is the normalized crop water productivity (g/m^2), Y is the dry mass of yield (g/m^2), hi is the harvest index (g/g) equal to the reference harvest index (hio, g/g) adjusted for water and temperature stress with f_{HI} (-), ET is the crop evapotranspiration, WP_{ET} is the ET crop water productivity (kg/m^3), and n is the number of sequential days spanning the growing period.

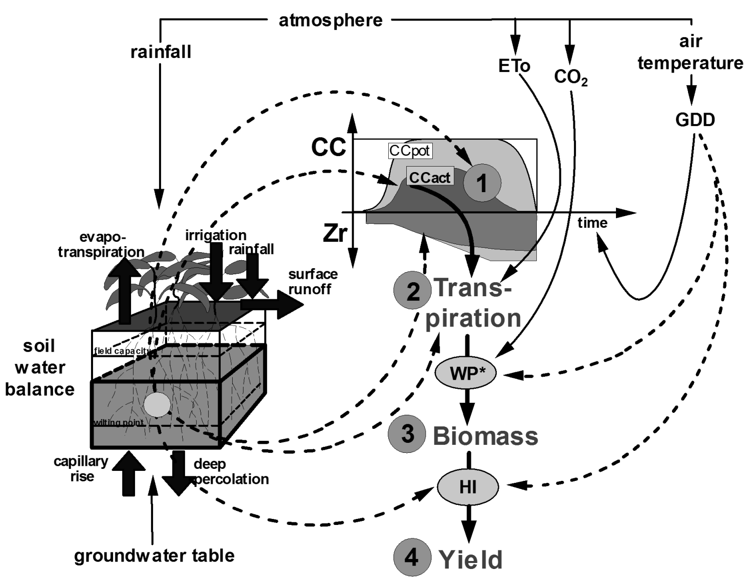


Figure 2.1: Calculation scheme of AquaCrop with indication of the four steps and the processes affected by water and temperature stress (dotted arrows).

AquaCrop simulation results of soil water content, green canopy cover, dry above-ground biomass production and crop yield can be evaluated against field observations by means of graphical displays as well as statistical performance indicators (Box 2.1).

Box 2.1: Model performance indicators

Following statistical performance indicators will be considered in this research:

(i) the coefficient of determination or squared Pearson's correlation coefficient (R^2, -):

$$R^2 = \left(\frac{\sum_{i=1}^{n}(O_i - \overline{O})(P_i - \overline{P})}{\sqrt{\sum_{i=1}^{n}(O_i - \overline{O})^2} \cdot \sqrt{\sum_{i=1}^{n}(P_i - \overline{P})^2}} \right) \tag{2.5}$$

(ii) the relative root-mean-square error (RRMSE, %) (Loague and Green, 1991):

$$\begin{aligned} RRMSE &= RMSE \cdot \frac{100}{\overline{O}} \\ &= \sqrt{\frac{\sum_{i=1}^{n}(O_i - P_i)^2}{n}} \cdot \frac{100}{\overline{O}} \end{aligned} \tag{2.6}$$

(iii) the Nash-Sutcliffe model efficiency (EF, -) (Nash and Sutcliffe, 1970):

$$EF = 1 - \frac{\sum_{i=1}^{n}(O_i - P_i)^2}{\sum_{i=1}^{n}(O_i - \overline{O})^2} \tag{2.7}$$

(iv) the relative model error (RME, %) (Bennett et al., 2013):

$$RME = \frac{\sum_{i=1}^{n}(O_i - P_i)}{\sum_{i=1}^{n}(O_i)} \cdot 100 \tag{2.8}$$

where O_i are the observed values, P_i are the predicted values, $\bar{O}$ is the mean of the observed values, $\bar{P}$ is the mean of the predicted values and n is the number of observations.

Model performance is considered better when R^2 and EF approach one, and when RRMSE and RME approach zero. Following Jamieson et al. (1991), model performance can be classified based on RRMSE values as excellent (RRMSE < 10 %), good (10 % < RRMSE < 20 %), fair (20 % < RRMSE < 30 %) and poor (RRMSE > 30 %).

2.4 Soil water balance

AquaCrop calculates the daily soil water content (SWC) in the soil profile by means of a soil water balance that keeps track of incoming (rainfall, irrigation, capillary rise) and outgoing (surface runoff, deep percolation, evaporation, crop transpiration) water fluxes (Figure 2.2). While rainfall and irrigation are user-specified inputs, other components of the soil water balance are calculated on the basis of the simulated crop canopy development as well as input of daily weather data, the depth of the groundwater table and soil characteristics.

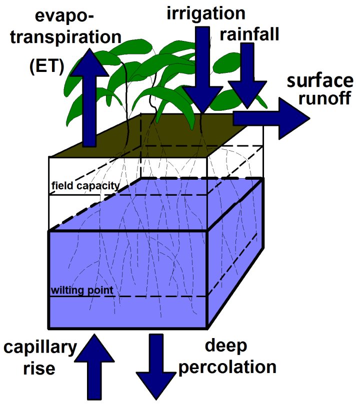


Figure 2.2: AquaCrop determines the soil water content in the root zone by calculating the soil water balance of incoming and outgoing water fluxes.

2.4.1 Crop transpiration and soil evaporation

Crop transpiration (Tr, Equation 2.1) and soil evaporation (E, Equation 2.9) are simulated as separate components of the soil water balance.

$$E_i = Kr_i \cdot Ke_i \cdot ET_{0_i} \tag{2.9}$$

where E_i is soil evaporation (mm/day) on day i, $\mathrm{Kr_i}$ is the evaporation reduction coefficient (-), $\mathrm{Ke_i}$ the evaporation coefficient (-) proportional to the non-covered soil fraction (1-CC), and ET_{0_i} is the reference evapotranspiration (mm/day).

Both components are proportional to the evaporative power of the atmosphere (ET_0) and simulated crop canopy cover via the crop transpiration ($\mathrm{Kc_{Tr}}$) and evaporation (Ke) coefficients, respectively (Equation 2.1 and 2.9). In addition, transpiration and evaporation are adjusted to the soil water content and corresponding water stress both indirectly via CC and directly via the soil water stress (Ks) or evaporation reduction (Kr) coefficient.

2.4.2 Surface runoff

Surface runoff (RO) is calculated using the USDA (1969) curve number (CN) equation:

$$RO_i = \begin{cases} 0 & \text{if } P_i \leq I_a \\ \dfrac{(P_i - I_a)^2}{P_i - I_a + S} & \text{if } P_i > I_a \end{cases} \tag{2.10}$$

where RO_i is surface runoff (mm/day) on day i, P_i is rainfall (mm/day), $\mathrm{I_a}$ is initial abstraction (mm) and S is surface storage capacity (mm). The surface storage capacity is derived from the surface runoff curve number (CN) with equation:

$$S = 254 \cdot \frac{CN}{100} - 1 \tag{2.11}$$

where CN is the surface runoff curve number (-) equal to the CN value selected by the user on the basis of soil and field management characteristics (CN_{input}), but adjusted to the soil water content during simulation:

$$CN = CN_{input} \cdot f_{CN,SWC} \tag{2.12}$$

where CN_{input} is the user-specified curve number (-) and $f_{CN,SWC}$ the correction factor for the soil water content in the top soil (by default set to a thickness of 0.3 m).

In the framework of this PhD research, the surface runoff calculation procedures have been revised according to latest advances on the curve number approach (Hawkins et al., 2009). The revised procedures as implemented in AquaCrop version 5.0 contain two major changes. First, the standard value of initial abstraction has been altered. Originally, AquaCrop applied the common assumption that $\mathrm{I_a}$ equals 20% of the storage capacity. However, it was found that 5% of S is a more appropriate value for general application (Hawkins et al., 2009). Consequently, this value was adopted as the new standard in AquaCrop version 5.0. It should be noted that also the CN input values should correspond to this assumption. Hence, CN values for $\mathrm{I_a}$=20%S, such as found in the curve number tables by USDA (2007), should be converted before they are used as AquaCrop input. This can be done by means of the conversion equation proposed by Jiang (2001):

$$CN_5 = \frac{100}{\left(1.879 \cdot (\frac{100}{CN_{20}} - 1)^{1.15}\right) + 1} \tag{2.13}$$

where CN_{20} and CN_5 are the surface runoff curve number under the assumption that $\mathrm{I_a}$ equals 20% and 5% respectively.

A second update was inspired by the fact that surface runoff depends as much on soil properties as on field surface management. Therefore, CN_{input} is no longer uniquely defined based on soil properties. In AquaCrop version 5.0 the CN specified as soil parameter (by default linked to the topsoil K_{sat}) is adjusted for field surface management (see Subsection 2.6.3).

$$CN_{input} = CN_{soil} \cdot f_{CN,mgmt} \tag{2.14}$$

where CN_{soil} is the input curve number as defined by soil properties (-) and $f_{CN,mgmt}$ is the adjustment factor for field surface management.

2.4.3 Deep percolation and capillary rise

To simulate vertical movement of water, the soil profile is divided into soil compartments of 10 cm by default. When the soil water content in one compartment exceeds field capacity, it drains to the next one at a rate controlled by a drainage coefficient (τ):

$$D_{z,i} = \tau(\theta_{SAT} - \theta_{FC}) \cdot \frac{e^{\theta_{z,i}-\theta_{FC}} - 1}{e^{\theta_{SAT}-\theta_{FC}} - 1} \tag{2.15}$$

where $D_{z,i}$ is the drainage at depth z on day i (mm/day), τ is the drainage coefficient (-) which is proportional to K_{sat}, $\theta_{z,i}$ is the actual soil water content at depth z (m^3/m^3), and θ_{SAT} and θ_{FC} are the soil water content at saturation and field capacity respectively (m^3/m^3). Drainage from the bottom compartment of the root zone is considered to be deep percolation to the groundwater.

The amount of water reaching the root zone via capillary rise depends on the soil properties and the depth of the groundwater table:

$$CR_i = exp\left(\frac{ln(z_{gwt,i}) - b}{a}\right) \tag{2.16}$$

where CR_i is the potential capillary rise on day i (mm/day), $z_{gwt,i}$ the user-specified depth of the ground water table below the root zone (m), and a and b soil parameters. Default values for these soil parameters are suggested by AquaCrop based on soil texture and soil hydraulic properties (K_{sat}) but can be further calibrated by the user.

The potential capillary rise as determined by Equation 2.16 is further adjusted to the soil water content to account for limitations to capillary rise when the soil is too wet (low potential gradient) or too dry (low hydraulic conductivity). The obtained potential capillary rise is divided over the soil compartments by filling up the bottom compartment of the soil profile to field capacity and proceeding upwards.

2.5 Crop response to abiotic factors

Next to environmental factors, AquaCrop considers various abiotic stresses including water stress, temperature stress, soil salinity stress and soil fertility stress. Crop parameters describing crop responses to these abiotic stresses are listed in Table A.2. The degree of stress is expressed using stress coefficients (Ks) which vary between 1 (no stress) and 0 (full stress). Ks is a multiplier of a certain target variable (e.g. B is the target of Ks_{b_i}). Stress curves or stress response functions determine how Ks changes in function of the stress indicator (e.g. air temperature expressed in growing degree days is the stress indicator for Ks_{b_i}). Stress curves have a linear, convex or logistic shape between the upper and lower threshold for which Ks equals 1 and 0 respectively.

2.5.1 Crop response to water stress

Crop response to water stress, either excess or shortage of water, is determined by several crop-specific water stress coefficients. Each Ks affects its own target variable and is linked to a crop- and process-specific threshold of soil water content in the root zone (SWC_r). Water shortage reduces speed of crop canopy development and root expansion, causes early crop senescence, reduces crop transpiration because of stomatal closure, and increases or decreases the reference harvest index depending on the timing of the water shortage. Water excess, on the other hand, might limit root expansion and reduces crop transpiration because of aeration problems (Figure 2.1).

2.5.2 Crop response to air temperature stress

Crop response to air temperature stress, i.e. both heat and cold stress, is determined by three stress coefficients. Biomass production is affected by cold stress (Ks_{b_i} in Equation 2.2), while pollination is affected by both cold and heat stress (Figure 2.1).

Additionally, air temperature also affects simulation of crop development when crop parameters are specified in growing degree days (GDD) (Figure 2.1). These GDD are calculated from the average air temperature taking into account crop-specific base and upper temperatures (tb and tup) which are the limits for crop canopy development. This means, for example, that crop development is slower when the average air temperature is low than when average air temperature is higher.

Finally, temperature stress is also considered indirectly via water stress. Since high temperatures often coincide with high ET_0 values, soil water is depleted faster and consequently water stress more prevalent in warm weather conditions. In addition, the water stress coefficients for canopy expansion, stomatal closure and early crop senescence are adjusted to ET_0 during simulation, so that the effect of water stress is stronger for days with high ET_0 values.

2.5.3 Crop response to CO_2 concentration

Crop biomass increases with increasing atmospheric CO_2 concentration ([CO_2]). The crop response to [CO_2] is simulated by means of f_{CO_2}, a correction factor that alters the normalized biomass water productivity (wp*) according to [CO_2], crop type (C4 crops are less responsive to [CO_2] than C3 crops) and the crop's sink strength (f_{sink}) (Vanuytrecht et al., 2011). This adjustment is especially crucial for simulation of future time horizons, as climate change affects crop production not only because of altered weather conditions but also through the CO_2 fertilization effect.

2.6 Agricultural management

AquaCrop considers the effect of agricultural management on the soil water balance and crop productivity. Various agricultural management practices can be simulated, either through adjustment of crop and soil parameters or directly by input of the field management practices' characteristics.

Since this manuscript focuses on rainfed agriculture, the extensive irrigation management options will not be discussed. For more information on irrigation management the reader is referred to the multitude of studies that demonstrate application of AquaCrop to study irrigation water requirements (e.g. Shrestha et al., 2014a; Palumbo et al., 2012), optimize irrigation management (e.g. Xiangxiang et al., 2013; García-Vila and Fereres, 2012) and develop deficit irrigation strategies (e.g. Geerts et al., 2010; García-Vila et al., 2009; Akhtar et al., 2013).

2.6.1 Crop management

Crop cultivar choice is considered through the non-conservative crop parameters. Cultivars might differ with respect to, for example, crop phenology (length of different phenological stages and growing cycle length), harvest index (landraces versus high-yielding cultivars) and rooting depth. Also, crop establishment practices are considered through the crop parameters. Canopy development depends on both the initial canopy cover which is linked to plant density and the crop establishment technique: sowing (e.g maize), transplanting (e.g. rice) or regrowth (e.g. grass). Also, the (trans)planting date is an input, either directly specified by the user or generated by AquaCrop based on weather input data according to user-specified rainfall or temperature criteria.

Jin et al. (2014) evaluated AquaCrop simulations of wheat production for various sowing dates. In addition, AquaCrop has been applied to optimize the timing of planting for barley and tef in Ethiopa (Abrha et al., 2012; Araya et al., 2012; Tsegay et al., 2015), maize in Zimbabwe (Mhizha et al., 2014; Nyakudya and Stroosnijder, 2014) and sunflower and soybean in Lebanon (Saab et al., 2014). Changing the planting date has also been investigated as a climate change adaptation strategy for wheat in Italy (Bird et al., 2016), tomatoes in Tunisia (Bird et al., 2016), and rice in Vietnam and the lower Mekong delta (Mainuddin et al., 2012, 2013; Shrestha et al., 2014b). Moreover, the effect of plant density was studied for rice in Tanzania (Katambara et al., 2013) and maize in Zimbabwe (Nyakudya and Stroosnijder, 2014). Production differences between maize cultivars with varying rooting depth were simulated with AquaCrop by Nyakudya and Stroosnijder (2014), whereas Mainuddin et al. (2012, 2013) simulated rice production differences in the lower Mekong delta where several varieties with varying harvest indices are cultivated.

2.6.2 Soil management

Soil management practices such as soil tillage, subsoiling and application of organic matter or soil conditioners (e.g. hydroabsorbents) focus on soil and water conservation aside from increasing crop production. As these practices affect soil texture and physical properties, they are considered through the user-specified soil input parameters. Adjustment of soil depth, TAW and K_{sat} in correspondence to soil management, affects simulation of the soil water content and consequently water stress affecting crop production. Also the presence of a hard soil layer (or breaking up this layer) can be simulated by specifying the depth of the restrictive soil layer. This impedes root expansion beyond that depth.

AquaCrop's performance to simulate soil water content and wheat production on stony soils in Italy was evaluated by Mekuria et al. (2016). Furthermore, Campi et al. (2015) studied the effect of organic- and clay-based soil amendments on maize production in Laos using AquaCrop.

2.6.3 Field surface management

AquaCrop considers field surface practices that reduce or impede surface runoff, including crop and planting arrangement, land preparation, and soil and water conservation practices (e.g. soil ridges). The effect of field surface management on surface runoff is considered by the adaptation of the soil dependent surface runoff curve number to management ($f_{CN,mgmt}$ in Equation 2.14). Built-in tables derived from CN tables by USDA (2007) support users to select a suitable adjustment factor. For practices that impede surface runoff, for example tied ridges, the fraction of rainfall that is surface runoff is considered to be zero, as long as the rainfall and irrigation volume does not exceed the infiltration rate of the topsoil. By addition of soil bunds, also the latter surface runoff will be inhibited and the infiltration excess water is stored on the soil surface between the bunds. Only water exceeding the user-specified bund height will give rise to surface runoff.

Next to tied ridges also other forms of rainwater harvesting can be simulated. Van Gaelen (2012) developed a procedure to simulate runoff agriculture, i.e. the practice where surface runoff is deprived from an uncropped or unproductive part of land ('catchment area') to concentrate it on another cropped part of land ('cropping area'). Runoff agriculture can be simulated with a two-step procedure. First, the amount of surface runoff generated on the catchment area is simulated. In a second step, the simulated runoff, scaled according to the catchment-to-cropping area ratio, is specified as additional irrigation input for simulation of the cropped field.

The Aquacrop calculation procedure for field surface management relies on the curve number method which has been thoroughly tested for many agricultural areas around the world. AquaCrop has been applied by Biazin and Stroosnijder (2012) to study the effect of tied ridges as water conservation strategy in the semi-arid Ethiopian highlands, and by Kikoyo and Nobert (2015) to study the effect of field surface practices as climate change adaptation strategies for maize cultivation in Uganda.

2.6.4 Mulches

Mulches such as straw, peat, sawdust, plastic and gravel influence crop growth and production due to their effect on soil temperature, soil organic matter content, soil physical properties, water availability, weed infestation, etc. Although mulches affect crop production in many ways, AquaCrop only considers the reduction of soil evaporation due to mulches. The reduction depends on the fraction of soil covered by mulch as well as the type of mulch, which are both considered to be constant over the growing season. Plastic mulches reduce soil evaporation from the covered soil by default by 100%, while organic mulches reduce soil evaporation by only 50%. Those default values can be adapted by the user if more detailed information is available.

The calculation procedure for evaporation reduction due to mulches was developed based on work by Allen et al. (1998). AquaCrop has been applied to study the effect of mulches as climate change adaptation strategy for maize production in Uganda (Kikoyo and Nobert, 2015) as well as tomato production in Tunisia and wheat production in Italy (Bird et al., 2016). Also Mekuria et al. (2016) applied AquaCrop to study the effect of mulches on maize crop water productivity in Laos.

2.6.5 Soil fertility management

The procedure to simulate crop response to soil fertility management is discussed and evaluated in Chapter 3.

2.6.6 Weed management

A preliminary procedure to simulate crop response to weed management, proposed by Abrha (2013), was implemented in a test version of AquaCrop 4.0. This procedure was revised and evaluated in the framework of this PhD research as presented in Chapter 4. The new improved procedure was implemented in a test version of AquaCrop 5.0, and will officially be released in a later AquaCrop version.

2.7 AquaCrop software

Software to run the AquaCrop model is distributed by FAO (2016). The standard software includes a graphical user-interface that supports preparation of input files, selection of parameters, running simulations, generation of output files and assessment of simulation results with the help of graphical displays. The plug-in software also executes the model, but without the graphical user-interface. This reduces model run times and facilitates implementation of AquaCrop in larger modelling frameworks.

As a result of continuous research, including this PhD research, the AquaCrop model has evolved throughout the years. Development and evaluation of the soil fertility procedure (Chapter 3), the weed management procedure (Chapter 4) and the surface runoff calculation procedure (Subsection 2.4.2) pointed out the need to update some of the existing AquaCrop calculation procedures and add new algorithms. Consequently, new versions of the AquaCrop software have been developed and released by FAO over the course of this PhD research. Table 2.1 presents an overview of adjustments to the agricultural management procedures implemented in AquaCrop version 4.0 and 5.0, the AquaCrop versions that were used in the following chapters. Input files created in AquaCrop version 4.0 are compatible with AquaCrop version 5.0. Also, simulation results will not change, as long as one adapts the surface runoff curve number to a value that matches with the new surface runoff procedure (Subsection 2.4.2).

Table 2.1: Overview of adjusted agricultural management procedures in AquaCrop version 4.0 and version 5.0. Test versions (marked with *) include a weed management module that was not yet officially released by FAO.

AquaCrop version	**4.0**	**4.0***	**5.0**	**5.0***
Applied in Chapter	3	5	6 & 7	4
Field surface management				
Runoff calculation with I_a=20%S	✓	✓		
Runoff calculation with I_a=5%S			✓	✓
Soil fertility management				
Procedure Chapter 3	✓	✓	✓	✓
Weed management				
Procedure Abrha (2013)		✓		
Procedure Chapter 4				✓

Chapter 3

Evaluation of the AquaCrop soil fertility management procedure

This chapter is based on:
Van Gaelen, H, Tsegay, A, Delbecque, N, Shrestha, N, Garcia, M, Fajardo, H, Miranda, R, Vanuytrecht, E, Abrha, B, Diels, J, and Raes, D (2015). A semi-quantitative approach for modelling crop response to soil fertility: Evaluation of the AquaCrop procedure. *The Journal of Agricultural Science*, 153 (7), 1218–1233. DOI: 10.1017/S0021859614000872

3.1 Introduction

Soil fertility exhaustion is widely acknowledged as a principal cause of low agricultural production in smallholder farming. The effects of soil fertility and the potential benefits of fertilizer application on crop production have traditionally been studied by means of experimental research. Unfortunately, field experiments tend to be laborious and time- and resource-consuming, and the results are often affected by the specific experimental set-up. For these reasons, present-day experimental research is often complemented with crop models, in order to study crop responses to soil fertility under various farming systems and environmental conditions (Myers, 2005). Crop models integrate different factors influencing crop production and contribute to the understanding of the interactions amongst these factors. Moreover, they enable very efficient long-term assessments to be made of numerous scenarios and fertility management strategies (Boote et al., 1996; Carberry et al., 2002) for both historical and future climatic conditions (Tubiello and Ewert, 2002).

Commonly used crop models, such as APSIM (Keating et al., 2003), CropSyst (Stöckle et al., 2003), DSSAT/CERES (Jones et al., 2003), STICS (Brisson et al., 2003) and WOFOST (Boogaard et al., 2014), typically make use of a nutrient-balance approach to consider the effects of soil fertility on crop production. Depending on the complexity of the model, environmental conditions, soil characteristics, the initial nutrient content of the soil, individual nutrient sources and their losses, and conversions of nutrients between different forms or 'pools' are taken into account in calculating the amounts of nutrients available to, or taken up by, the crop. In this way, crop productivity and growth processes can be related to the nutrient content of the soil, to nutrient uptake and to the nutrient content of specific plant organs. One of the disadvantages of such a detailed approach is the requirement for a vast input of data. Moreover, the nutrient-balances are mostly calculated for selected nutrients (often merely nitrogen), which are not always the nutrients that are the most limiting to crop growth and productivity (Probert and Keating, 2000; Probert, 2004; Brisson et al., 2003); in addition, the release of nutrients from organic fertilizers such as crop residues or manure is difficult to quantify but is nevertheless crucial for the estimation of the nutrient-balance (Probert and Dimes, 2004; Gijsman et al., 2002). Finally, the relationships between nutrients and crop production have mostly been developed for a specific crop type and hence the models are not widely applicable. These disadvantages clearly hamper the application of detailed, nutrient-balance-based crop models to smallholder farming systems in tropical and sub-tropical regions, where a wide variety of crops are grown (in rotation, or by intercropping), where organic fertilizers are the predominant soil fertility management strategy, and where other nutrients besides nitrogen (e.g. phosphorus) limit crop production (Delve et al., 2009; Whitbread et al., 2010).

An alternative to the nutrient-balance approach consists of modelling the effects of soil fertility on crop development and production in a semi-quantitative way. Such a semi-quantitative approach was implemented in AquaCrop (Hsiao et al., 2009; Steduto et al., 2009; Raes et al., 2009; Vanuytrecht et al., 2014a), the crop water productivity model developed by the Food and Agriculture Organization of the United Nations (FAO), and has been updated in the latest version, AquaCrop version 4.0 (Raes et al., 2012). In contrast to other models, nutrient cycles or balances are not considered explicitly in AquaCrop, but soil fertility stress is determined by its expected effects on crop biomass production. The calculation procedure does not distinguish between different nutrients and it is identical for all crops; only the calibration of the model is crop- and case-specific. Furthermore, AquaCrop integrates the effects of various production-limiting factors – including climatic factors, soil water stress, soil salinity stress and field management – with soil fertility stress. Within this integrated approach, between-stress interactions are taken into account, thereby allowing realistic yield simulations to be made.

In this chapter, the semi-quantitative approach of AquaCrop (version 4.0) to the simulation of crop responses to soil fertility is described extensively for the first time and evaluated for different crops under diverse environmental and meteorological conditions. The study aims to evaluate the performance of AquaCrop's fertility response algorithms in simulating not only final yield production, but also the soil water balance, canopy development, and dry above-ground biomass for various soil fertility levels, both in the presence and in the absence of soil water stress. By providing a reliable alternative to commonly used soil nutrient-balance approaches, the semi-quantitative approach will contribute to, rather than replace, the existing diversity of simulation approaches for crop responses to limited soil fertility. The semi-quantitative approach is particularly applicable in circumstances where detailed observations of soil nutrient conditions are unavailable.

3.2 Methodology

3.2.1 The semi-quantitative approach of AquaCrop

Instead of using a nutrient-balance, AquaCrop proposes a semi-quantitative assessment to determine the degree of stress that a crop experiences from nutrient deficiencies. This semi-quantitative measure corresponds to the maximum relative dry above-ground biomass (B_{rel}) that can be expected in a soil fertility stressed environment with reference to stress-free conditions (Equation 3.1). B_{rel} ranges from 0%, corresponding to complete crop failure from nutrient deficiency, to 100%, indicating no nutrient stress.

$$B_{rel} = \frac{B_{stress}}{B_{ref}} \cdot 100 \tag{3.1}$$

where B_{rel} is the maximum relative dry above-ground biomass (%), B_{stress} is the total dry above-ground biomass at the end of the growing season in a field with soil fertility stress, and B_{ref} is the total dry above-ground biomass at the end of the growing season in a field without soil fertility stress. Both B_{stress} and B_{ref} are to be recorded in well watered fields (no soil water stress) and free of any other stress factors, such as weeds, pests, diseases and salinity.

Being a semi-quantitative input parameter, B_{rel} can be obtained easily. It is the maximum biomass that can be produced under the governing local conditions in a field that is only affected by soil fertility stress (the 'soil fertility stressed' field) in a good rainy year, or under irrigation when there is no water stress (B_{stress}). This biomass may be available from statistical reports or from indigenous farmer knowledge. The biomass is then expressed as a percentage of the biomass produced under stress-free conditions (B_{ref}), which can be obtained from nearby experimental fields, from published potential yields, or through the application of a full nutrient strip in one part of a farmer's field. In addition, model simulations can provide an estimation of the biomass for the local farming conditions under stress-free conditions (the 'reference' field).

When crop production is not affected by soil fertility stress, AquaCrop simulates crop productivity using a four-step process as discussed in Section 2.3. First, green crop canopy cover (CC) is simulated. In a second step, crop transpiration (Tr) is simulated considering reference evapotranspiration (ET_0) and the simulated canopy cover. Next, crop transpiration is converted into dry above-ground biomass production (B). In a final step, crop biomass is converted to crop yield (Y) by means of the harvest index (hi). During this four-step simulation process, the model accounts for the effect of various abiotic stresses (Section 2.5), including water stress, temperature stress, soil salinity stress and soil fertility stress.

In AquaCrop, the overall effect of soil fertility stress on crop production is simulated as the result of an integration of its effects on canopy cover development and biomass production. First, AquaCrop mimics the effect of soil fertility stress on the canopy cover, according to what can be observed in soil fertility stressed fields (Walburg et al., 1981; Albrizio and Steduto, 2005). For this reason, three adaptations to the canopy cover development are introduced (Figure 3.1): (i) reduced canopy expansion, and consequently slower canopy development; (ii) reduced CC_x, and hence a less dense canopy; and (iii) steady decline of the canopy cover once CC_x is reached at mid-season. Mimicking canopy cover development under soil fertility stress is a crucial feature of the semi-quantitative AquaCrop procedure because it enables a correct simulation to be made of transpiration and soil water balance. Secondly, based on observations from field experiments reported by Steduto and Albrizio (2005), the effect of soil fertility stress on daily biomass production is simulated by a reduction in wp*. As the reservoir of soil nutrients gradually becomes depleted during crop development, the correction to wp* gradually increases (therefore, wp* itself is more strongly reduced) as more biomass is produced (Figure 3.2). This correction to wp* was inspired by Geerts (2008) who reported, on the basis of experimental work with quinoa in the Bolivian Altiplano, that AquaCrop would more accurately represent the true situation if wp* was reduced once a certain amount of biomass had been produced and nutrients had become limiting.

To simulate these four crop responses to soil fertility stress, AquaCrop uses four stress coefficients, i.e. for canopy expansion ($\mathrm{Ks_{exp,f}}$), for maximum canopy cover ($\mathrm{Ks_{CC_x}}$), for canopy decline ($\mathrm{f_{CDecline}}$) and for biomass water productivity ($\mathrm{Ks_{wp}}$). These stress coefficients range from 1 (no stress) to 0 (full stress). For every stress coefficient, a stress curve (Figure 3.3a) defines the relationship between the level of soil fertility stress and the reduction of the target crop parameter (canopy growth coefficient (cgc), CC_x, wp* and CC, respectively) that is affected by soil fertility stress. The shape of the stress curve can be convex, concave or linear. Since the stress coefficient is always equal to 1 for 0% soil fertility stress and 0 for 100% soil fertility stress, the shape of the curve is determined by the position of one additional point that is determined by calibration, i.e. 'the calibration point' (Figure 3.3a). As mentioned above, even though the fertility stress simulation procedure is the same for different

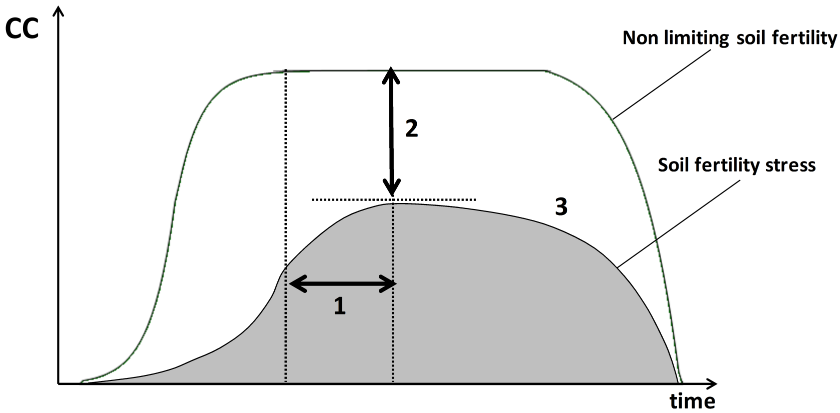


Figure 3.1: Soil fertility stress affects green canopy cover (CC) development by means of (1) a reduction of the canopy growth coefficient (cgc) and hence slower canopy development, (2) a reduction of CC_x and hence a less dense canopy and (3) a steady decline in canopy cover once CC_x is reached at mid-season.

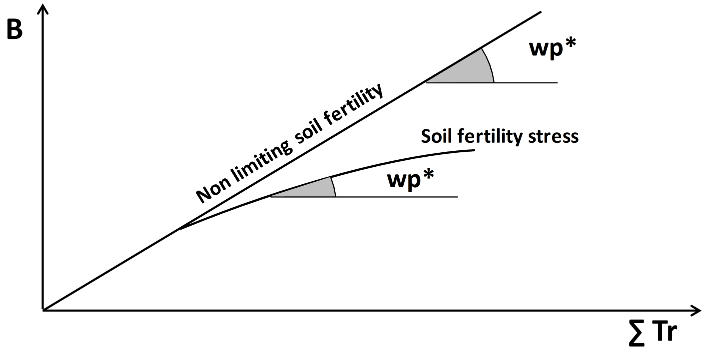


Figure 3.2: Soil fertility stress gradually reduces biomass water productivity (wp*) throughout the season as cumulative biomass (B) increases and the soil nutrient reservoir becomes depleted. The x-axis representing cumulative daily transpiration (ΣTr) could also been seen as an axis representing time.

crops, the crop response to soil fertility is specific to the crop type and to the environmental conditions under which the crop is cultivated, including climate and soil type. Therefore, the crop response to soil fertility stress cannot be described using conservative crop parameters (independent of location, crop cultivar or management practice) but requires calibration for each case.

To facilitate the calibration of the four stress curves, an autocalibration procedure that simultaneously fixes the four calibration points is incorporated in the latest AquaCrop software (version 4.0 and 5.0). This autocalibration procedure requires field observations of CC_x and B_{rel} and a qualitative description of the observed canopy decline during the season for a 'soil fertility stressed' calibration field in comparison to a 'reference' field (no soil fertility stress). To avoid interference and interaction with other stress factors during calibration, both fields need to be free of soil water stress and salinity stress, as well as of diseases, weeds and pests. Furthermore, the autocalibration procedure assumes that the soil fertility stress level in the calibration field equals 100-B_{rel}. Using a local search algorithm within the ranges that match the field observation input, the autocalibration procedure evaluates several combinations of values for the four calibration points. The combination of four calibration points that results in a biomass simulation as close as possible to the specified B_{rel} is retained as the procedure's outcome. After autocalibration a user can still manually refine the calibrated shapes of the stress curves if deemed necessary.

Next, based on the four calibrated stress curves (Figure 3.3a), the expected canopy development and reduction of biomass are calculated for every level of soil fertility stress between full stress and no stress, assuming no water stress. This results in the determination of the relative biomass-soil fertility stress relation (Figure 3.3b). This relationship is not linear because (i) the shapes of the four stress curves are mostly non-linear, (ii) the shapes of the stress curves differ amongst the four stress coefficients, and (iii) the effect of soil fertility stress on wp* increases when biomass increases.

Once the crop response to soil fertility stress is calibrated, crop production can be simulated for specified soil fertility levels under various environmental and management conditions. In order to perform a simulation, the user needs to specify the soil fertility level in terms of B_{rel} (ranging from 20 to 100%) or to select a class between 'non-limiting' and 'very poor' biomass production, which is linked to a default B_{rel} value. In the model, the user-specified input of B_{rel} is translated into a soil fertility stress level by means of the calibrated biomass – soil fertility stress relationship (Figure 3.3b). Next, this soil fertility stress level is linked to the corresponding stress coefficients so that the four target parameters are adapted accordingly. Additionally, AquaCrop accounts for other stresses affecting biomass production by making a dynamic adjustment of the soil fertility stress level at every time step. If, for example, soil water stress limits biomass production during time step i, the simulated B_{rel} during time

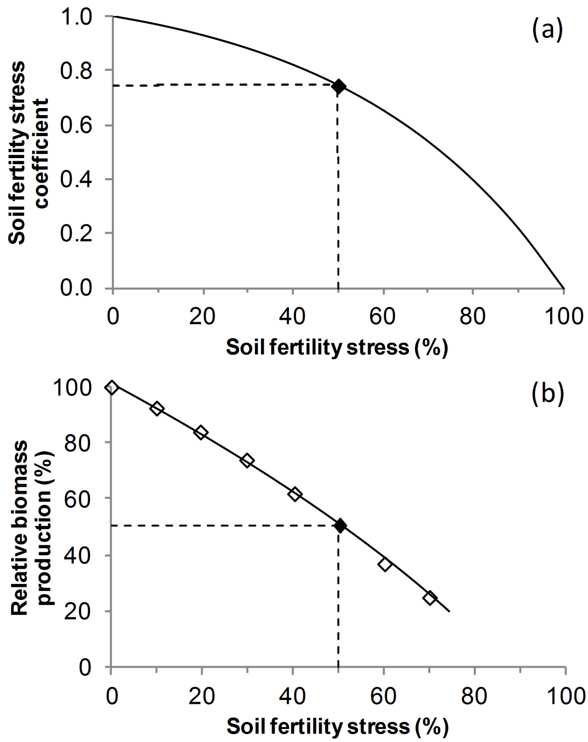


Figure 3.3: Four stress curves (of the type shown in a), which represent the relationships between soil fertility stress and the four soil fertility stress coefficients, determine the relationship between relative biomass production (B_{rel}) and soil fertility stress (shown in b). The calibration point (♦) determines the shape of a stress curve.

step i will be lower than the B_{rel} that would be expected during that time step on the basis of soil fertility stress alone ($B_{rel,input}$). Consequently, AquaCrop will reduce the soil fertility stress during time step i+1 in such a way that $B_{rel,input}$ could theoretically still be reached at the end of the crop cycle. This dynamic adjustment is justified because it can be assumed that the limitation of biomass production during time step i leaves more nutrients in the soil.

3.2.2 Field experiments

The semi-quantitative AquaCrop approach was tested against: (i) three years of experimental data for fields of tef (*Eragrostis tef* (Zucc.) Trotter) in the drought-prone degraded highlands of Tigray in northern Ethiopia, (ii) two years of experimental data for fields of maize (*Zea mays* L.) and wheat (*Triticum* *aestivum* L.) in the humid plains of the central Terai in Nepal, and (iii) two years of experimental data for fields of quinoa (*Chenopodium quinoa* Willd.) in the semi-arid Bolivian Altiplano. Table 3.1 presents a summary of the environmental conditions at the experimental sites. All experiments were set up with a (factorial) randomized complete block design, with the water treatment as main factor and the soil fertility treatment as sub-factor. In rainfed (RF) and deficit irrigated (DI) treatments, some degree of water stress was apparent, whereas in the fully irrigated (IR) treatment crops were maintained free of any water stress. Fertility treatments corresponded to applications of 0% (T0), 50% (T50), 100% (T100) and 150% (T150) of the (national) recommended fertilizer dose (see Table 3.1 for local recommendations). At all the experimental sites, the plots were regularly weeded and kept free from pests and diseases throughout the growing season. The following information was recorded: local daily weather data, soil water content in the root zone, the soil texture and physical characteristics, irrigation applications, fertilizer applications, crop development (green canopy cover development, monitored by overhead digital photographs), crop phenology (time of sowing, emergence, CC_x, flowering, senescence and maturity), effective rooting depth, intermediate and the final dry above-ground biomass, and the final grain yield. More detailed information on the set-up and data collection for the field experiments is described by Tsegay et al. (2012) for Ethiopia, by Shrestha et al. (2013b) for Nepal, and by Geerts et al. (2008) for Bolivia.

Table 3.1: Three experimental sites with the experimental set-up and environmental conditions (average climatic conditions according to FAO (2005)). Experiments were set up with a randomized complete block design (RCBD) or a factorial randomized complete block design (FRCBD). Water treatments consist of rainfed (RF), deficit irrigation (DI) and full irrigation (IR). Fertility treatments correspond to application of 0% (T0), 50% (T50), 100% (T100) and 150% (T150) of the (national) recommended fertilizer dose.

Experimental site	**Dejen**	**Maiquiha**	**Chitwan**	**Patacamaya**
Country	Ethiopia	Ethiopia	Nepal	Bolivia
Coordinates	13°20’ N, 39°22’ E	13°48’ N, 39°27’ E	27°36’ N, 84°24’ E	17°14’ S, 67°55’ W
Altitude (m a.s.l.)	2128	2078	160	3793
Environmental conditions				
Soil type	Loam, silty loam, sandy loam	Silty loam	Sandy loam	Silty loam
Aridity	Semi-arid	Semi-arid	Humid	Semi-arid
Annual rainfall (mm)	620	620	1870	403
Annual ET_0 (mm)	1497	1497	1219	1208
Experimental set-up				
Years	2008-2010	2009	2009-2011	2006/07, 2009/10
Number of seasons	3	1	2	2
Design	FRCBD	FRCBD	RCBD/ FRCBD	FRCBD
Crops	tef	tef	wheat, maize	quinoa
Water treatments	RF, IR	RF, IR	RF, DI, IR	RF, DI, IR
Fertility treatments	T0, T50, T100*	T0, T50, T100*	T0, T100, T150*	T0, T50, T100*

* T0, T50, T100, T150: Application of 0%, 50%, 100% and 150% of the (national) recommended fertilizer dose

T100 tef: 60 kg/ha N and 26 kg/ha P on heavy soils and 40 kg/ha N and 26 kg/ha P on light soil (EARO, 2002)

T100 maize: 120 kg/ha N, 60 kg/ha P, 40 kg/ha K (MOAC, 2010)

T100 wheat: 100 kg/ha N, 50 kg/ha P, 25 kg/ha K (MOAC, 2010)

T100 quinoa: 30 t/ha organic fertilizer (sheep manure) (Miranda et al., 2012)

3.2.3 Calibration and evaluation of the semi-quantitative AquaCrop procedure

As a starting point for the calibration of crop responses to soil fertility stress, the default crop parameters of AquaCrop version 4.0 (Table A.3) were used for all four crops. The non-conservative cultivar-specific crop parameters, describing the crop phenology, were fine-tuned to match the local cultivar and environmental conditions. The resulting crop files described canopy development, biomass production and yield under both optimal agronomic conditions and water stress, but not at this stage the crop responses to soil fertility stress.

The crop response to soil fertility stress was calibrated based on field observations during the rainy season of 2010 for tef, during the dry season of 2010/11 for maize and wheat, and during the growing season of 2009/10 for quinoa. Tef was only calibrated for one of the experimental sites (Dejen), because it was assumed that the soil fertility and environmental conditions for both sites would be similar, and that the crop would therefore respond identically to soil fertility stress at both sites. In the autocalibration procedure (Table 3.2), observations of canopy cover development and of biomass for plots not experiencing water stress but undergoing full soil fertility stress (IR-T0) were compared to observations for plots undergoing neither water stress nor fertility stress (IR-T100 for Ethiopia and Bolivia and IR-T150 for Nepal). For the tef and quinoa experiments, the (national) recommended fertilizer dose (T100) was taken as the ‘reference’, because the T100 treatment relieved crops from fertility stress. In contrast, T100 cannot represent non limiting soil fertility for the maize and wheat experiments in Nepal, because production increases for maize and wheat were observed with fertilizer doses that exceeded the national recommended dose. For this reason, T150 was used as the reference for the calibration of the maize and wheat responses to soil fertility stress in Nepal.

The calibrated crop response to soil fertility stress for each crop (Table 3.2) was evaluated with the remaining, independent field datasets covering the different experimental sites (for tef), the different growing seasons, and the various water and fertility treatments. The observed B_{rel} for the non water-stressed treatments was used as input, but no alterations to the calibrated crop responses (Table 3.2) were made; thus the biomass – soil fertility stress relation (Figure 3.3b) was applied as described in the calculation procedure above. For both calibration and evaluation, the environmental conditions at the experimental sites were used as the inputs for the AquaCrop model.

The fit between the observed and simulated soil water content in the root zone (SWC_r), canopy cover, biomass and yield was assessed by a combination of graphical displays (plots of simulated versus observed values) and three

Table 3.2: The relative dry above-ground biomass production (B_{rel}), maximum canopy cover (CC_x) and canopy decline in the season as observed for the soil fertility stressed calibration plots (IR-T0) of tef, maize, wheat and quinoa together with the resulting calibrated local effect of soil fertility stress on canopy development (canopy growth coefficient (cgc), CC_x, canopy decline) and biomass water productivity (wp*).

Crop **Calibration location**		Tef Dejen	Maize Chitwan	Wheat Chitwan	Quinoa Patacamaya
Input for calibration					
B_{rel}	(%)	66	53	44	50
CC_x	(%)	66	52	50	44
Canopy decline	(-)	medium	medium	medium	medium
Results of calibration					
cgc reduction	(%)	15	15	39	36
CC_x reduction	(%)	19	31	44	41
Average canopy decline	(%/d)	0.78	0.85	0.28	0.19
wp* reduction	(%)	19	31	50	19

statistical indicators presented in Box 2.1: R^2, RRMSE and EF. Model performance was qualified based on RRMSE values following Jamieson et al. (1991). Special attention was paid to the performance of the model under conditions in which soil water stress coincided with soil fertility stress. For this purpose, the performance of the model was also evaluated using only the RF and DI plots.

3.3 Results

This section discusses the performance of the model in simulating crop responses to soil fertility stress, with a focus on the RRMSE values because they give a clear indication of the magnitude of the deviation between the model's simulation results and the actual observations. Additionally, Table 3.3 (calibration) and Table 3.4 (evaluation) present the R^2 and EF values.

3.3.1 Calibration of the crop responses to soil fertility stress

Crops were calibrated for different local soil fertility stress conditions (Table 3.2). Soil fertility stress in the calibration fields was the highest for wheat (B_{rel} 44%) and the lowest for tef (B_{rel} 66%), with maize and quinoa being intermediate (B_{rel} 50-53%). The calibration results (Table 3.2) clearly show how the four crops in their specific environments responded very differently to the local nutrient limitations. For example, a soil fertility level B_{rel} of about 50% resulted in a greater reduction in wp* and in canopy decline in maize than in quinoa. By contrast, the reduction in crop development and CC_x was greater in quinoa than in maize. The calibrated effect of soil fertility on CC and wp* (Table 3.2) resulted in an acceptable simulation of SWC_r and of the overall development of CC and B throughout the crop cycle for the soil fertility stressed calibration plots (IR-T0) (Table 3.3). The model performed excellent in simulating SWC_r with RRMSE values below 10% for all crops. For CC and B, the model performance was more variable, with RRMSE values mostly above 10%. The model predicted CC with a RRMSE of about 16% for tef, but the RRMSE increased to 20-24% for wheat and maize. CC predictions could not be evaluated for quinoa, due to a lack of observations. With a RRMSE value of about 9%, the best prediction of B was obtained for maize, followed by tef and wheat, for which RRMSE values were 12 and 14% respectively. For quinoa, B was predicted with a RRMSE value of about 25%. Generally, the model calibration was most accurate (based on the RRMSE values for SWC_r, CC and B) for maize and tef, followed by wheat and quinoa.

Table 3.3: Relative root-mean-square error (RRMSE), Nash-Sutcliffe model efficiency (EF) and coefficient of determination (R^2) for n number of observationss of the soil water content in the root zone, canopy cover and dry above-ground biomass during the growing season of the soil fertility stressed calibration plots (IR-T0). Dashes indicate that observations for performance assessment were unavailable.

Variable	**Statistic**		**Tef**	**Maize**	**Wheat**	**Quinoa**
Soil water content	n	(-)	15	5	8	5
	RRMSE	(%)	5.6	2.6	6.7	9.6
	EF	(-)	0.74	0.85	0.81	0.97
	R^2	(-)	0.75	0.99	0.87	0.98
Canopy cover	n	(-)	12	6	9	-
	RRMSE	(%)	15.8	23.5	20.1	-
	EF	(-)	0.94	0.81	0.76	-
	R^2	(-)	0.97	0.91	0.87	-
Biomass season	n	(-)	8	6	8	11
	RRMSE	(%)	11.9	9.3	14.2	25.2
	EF	(-)	0.94	0.98	0.94	0.92
	R^2	(-)	0.96	1	0.95	0.97

3.3.2 Evaluation of crop responses to soil fertility stress

The calibrated model performed well in simulating SWC_r, CC, B and Y for the remaining independent evaluation plots under different soil water stress levels (IR, DI and RF) and soil fertility stress levels (T0, T50 and T100 (only for Nepal)) (Table 3.4). The performance of the model in its simulation of CC was variable, with a RRMSE as high as 34% for maize, although lower RRMSE values were obtained both for tef (23%) and for wheat (12%). For maize, this was probably a reflection of the relatively poor CC calibration (Table 3.3), whereas for wheat it reflected the good CC calibration. Despite the CC predictions, SWC_r was the most accurately predicted of all the variables, with RRMSE values of between 6 and 13%. Together, the accuracy of the simulations of CC and SWC_r and the corresponding soil water stress levels determined the accuracy of prediction of B during the growing season and at maturity. Figure 3.4 illustrates that the effect of different soil fertility stress levels on the development of CC and B in a well-watered wheat field was well described by AquaCrop. The AquaCrop simulations clearly captured the slow canopy development, lower CC_x, early canopy decline and lower biomass production under different soil fertility levels as they were observed in the field. The development of B during the season, as well as the final value of B, was predicted most accurately for wheat, followed by maize; the final value of B was predicted with a RRMSE of only 4% for wheat, and of 12% for maize. For quinoa and tef, the RRMSE values for the final B predictions were 18 and 24%, respectively. Finally, Y was one of the most accurately predicted variables, second only to SWC_r. For maize, the prediction of yield was excellent, with a RRSME of only 7%. With RRMSE values of 10% for wheat, 16% for quinoa and 19% for tef, the model resulted in good final Y predictions for all crops. This is also illustrated in Figure 3.5. In general, the model performed most accurately (based on the RRMSE values) for maize (for which it produced the best predictions for Y and SWC_r) and wheat (for which it produced the best predictions for B and CC), followed by quinoa and by tef.

Table 3.4: Relative root-mean-square error (RRMSE), Nash-Sutcliffe model efficiency (EF) and coefficient of determination (R^2) for n number of observations of the soil water content in the root zone, canopy cover, dry above-ground biomass (*B*) during the season and at phenological maturity and the final dry grain yield of the evaluation plots with soil fertility stress (T0 and T50 for tef and quinoa, T0 and T100 for maize and wheat). The left-hand statistics include all water treatments (RF, DI and IR), while the right-hand statistics only include the plots with water stress (RF and DI).

			All water treatments				**Water-stressed treatments**			
Variable	**Statistic**		Tef	Maize	Wheat	Quinoa	Tef	Maize	Wheat	Quinoa
Soil water content	n	(-)	189	39	60	15	98	26	40	10
	RRMSE	(%)	11	5.8	9.4	13.3	12.2	6.5	10.1	16.5
	EF	(-)	0.9	0.89	0.64	0.93	0.9	0.88	0.63	0.89
	R^2	(-)	0.9	0.89	0.9	0.93	0.9	0.91	0.91	0.89
Canopy cover	n	(-)	131	42	60	-	65	28	49	-
	RRMSE	(%)	22.7	34.2	6.7	-	26.8	38.1	12	-
	EF	(-)	0.9	0.74	0.93	-	0.89	0.68	0.93	-
	R^2	(-)	0.92	0.82	0.95	-	0.91	0.82	0.95	-
B season	n	(-)	96	39	51	43	50	26	34	30
	RRMSE	(%)	19.6	15.9	13.1	22.4	19.2	18.2	14.6	22.6
	EF	(-)	0.86	0.96	0.96	0.93	0.77	0.95	0.95	0.91
	R^2	(-)	0.88	0.97	0.96	0.95	0.87	0.96	0.95	0.95
B maturity	n	(-)	15	6	6	13	8	4	4	10
	RRMSE	(%)	23.6	11.8	3.9	18.3	19.6	13.3	3.5	15.2
	EF	(-)	0.71	0.83	0.96	0.76	0.25	0.79	0.97	0.69
	R^2	(-)	0.77	0.95	0.96	0.91	0.82	0.97	0.98	0.87
Yield	n	(-)	15	6	6	13	8	4	4	10
	RRMSE	(%)	19.1	7.2	10.3	16.3	34	10.7	11.9	13
	EF	(-)	0.84	0.97	0.74	0.71	-0.5	0.96	0.73	0.84
	R^2	(-)	0.85	0.99	0.77	0.81	0.21	0.99	0.93	0.86

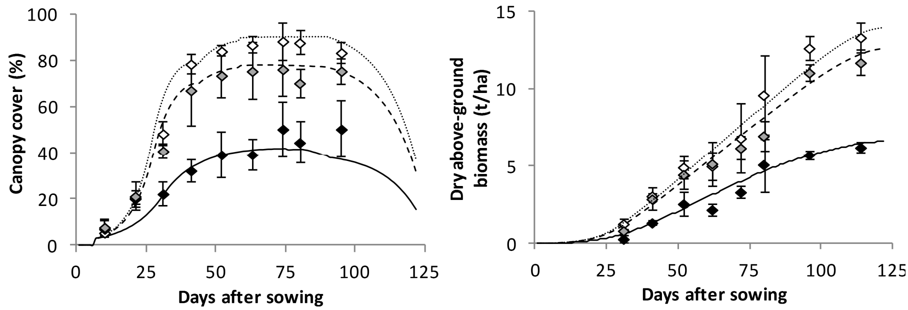


Figure 3.4: Simulated (lines) and observed (symbols) canopy cover (left) and dry above-ground biomass (right) of irrigated wheat in Chitwan during the season of 2010/11. Canopy development and biomass build-up are affected by the soil fertility level: non limiting soil fertility T150 (dotted line, open symbol), full soil fertility stress T0 (full line, black symbol), and fertility treatment with 100% of the national recommended fertilizer dose T100 (dashed line, grey symbol). Error bars indicate ± standard deviation for three replications (n=3).

3.3.3 Performance of the model under combined soil fertility stress and water stress

When both soil fertility stress and water stress were prevalent, AquaCrop was still able to predict the evolution of SWC_r (Figure 3.6), CC (Figure 3.7) and B (Figure 3.8) accurately during the growing season. The statistics for the water-stressed plots only (DI and RF) in Table 3.4 show that the fit is approximately as good as when all the water treatments (IR, DI and RF) are included. Compared to the evaluation for all the water treatments, the RRMSE values increased by only 0.7-3.2% for SWC_r, 0.1-4% for CC, and 0.2-2.3% for B, for the water-stressed plots alone. For B, in the cases of tef and quinoa, the performance of the model at maturity was even better when only the water-stressed conditions were taken into account (RRMSE decreased by 3-4%). The model predicted Y under combined water stress and soil fertility stress with a RRMSE of between 11 and 13% for maize, wheat and quinoa. The RRMSE only increased by 1.6% (wheat) and by 3.5% (maize), and for quinoa it even decreased (by about 3%). For tef, on the other hand, the predictions of Y under combined soil water stress and soil fertility stress were rather poor with a RRMSE as high as 34%. This may be due to inaccurate simulation of the effect of water stress on the harvest index. Finally, Figure 3.5 also shows how, with its semi-quantitative soil fertility approach, AquaCrop is able to predict values for grain production that range from as little as 0.5 t/ha to more than 4 t/ha as a result of the various climatic, agronomic and environmental conditions and from the combinations of soil fertility and soil water stress levels.

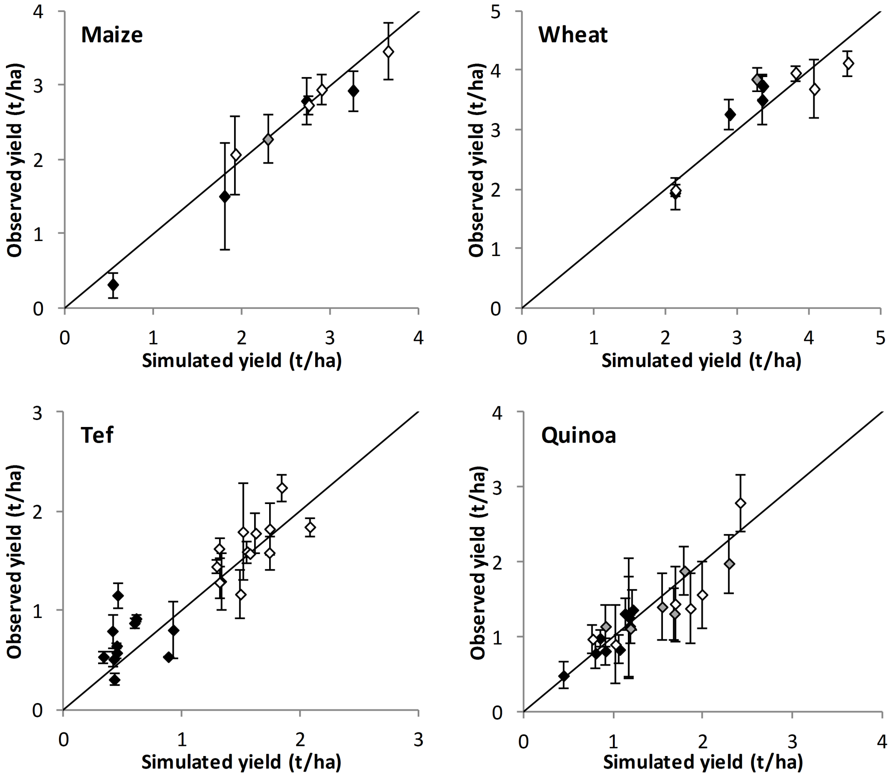


Figure 3.5: Observed versus simulated dry grain yield for maize and wheat in Nepal, for tef in Ethiopia and for quinoa in Bolivia for all simulated environmental conditions, soil fertility levels (T0, T50, T100 and T150) and water treatments (IR in white symbols, DI in grey symbols and RF in black symbols). Error bars indicate ± standard deviation for three replications (n=3).

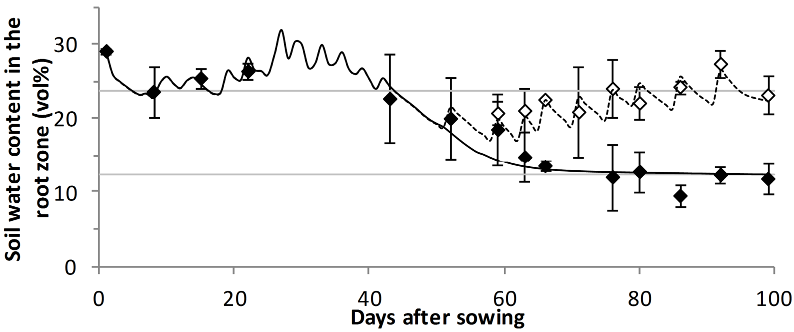


Figure 3.6: Simulated (lines) and observed (symbols) soil water content in the root zone for tef under soil fertility stress (T50) in Dejen during the season of 2010. Both irrigated (IR, dotted line, open symbol) and rainfed (RF, full line, filled symbol) soil water content are well simulated. Horizontal grey lines indicate the soil water content at field capacity (top line) and permanent wilting point (bottom line). Error bars indicate ± standard deviation for three replications (n=3).

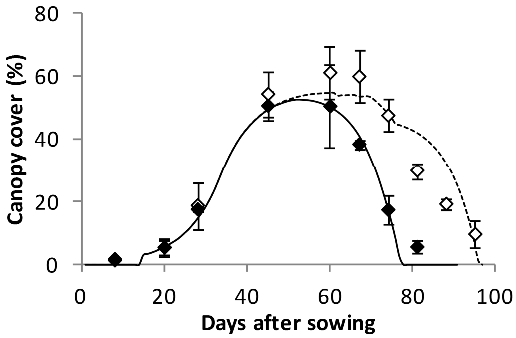


Figure 3.7: Simulated (lines) and observed (symbols) green canopy cover for tef under soil fertility stress (T0) in Maiquiha during the season of 2009. Both irrigated (IR, dotted line, open symbol) and rainfed (RF, full line, filled symbol) canopy cover development under soil fertility stress are well simulated. Error bars indicate ± standard deviation for three replications (n=3).

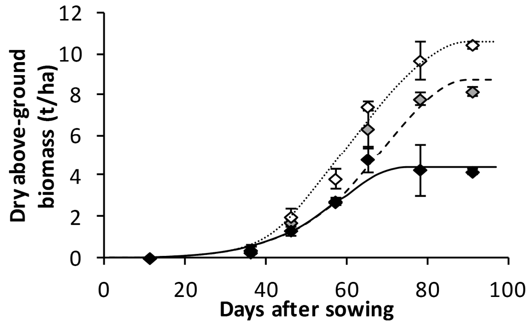


Figure 3.8: Simulated (lines) and observed (symbols) dry above-ground biomass for maize in Chitwan during the season of 2009/10. Irrigated (IR, dotted line, open symbol), deficit irrigated (DI, dashed line, grey symbol) and rainfed (RF, full line, black symbol) biomass production under soil fertility stress (T100) are all well simulated. Error bars indicate ± standard deviation for three replications (n=3).

3.4 Discussion

3.4.1 Performance of the semi-quantitative AquaCrop approach

Because the semi-quantitative AquaCrop procedure uses the relative biomass of a soil fertility stressed field compared to that of a reference field (B_{rel}) as the input from which to determine the soil fertility stress coefficients, it appears obvious that the final biomass, and consequently the yield simulations, for fertility stressed fields match the observations that are made in the absence of water stress. Nevertheless, the present study has shown that the semi-quantitative AquaCrop soil fertility procedure provides realistic results; not only were the final biomass and the yield simulated with acceptable accuracy (RRMSE of 4-24% for B at maturity and 7-19% for Y), but the soil water content, canopy cover and biomass development during the growing season were all also simulated with satisfactory accuracy (RRMSE of 6-13% for SWC_r, 12-34% for CC and 13-22% for B) – and even for stress levels for which the model had not been calibrated. Moreover, it has been shown that AquaCrop can provide good indicative values for final biomass (RRMSE of 4-15%) and for yield (RRMSE of 11-13%) of maize, wheat and quinoa when crop production is affected by both soil fertility stress and soil water stress. In the case of tef, although biomass production was well simulated (RRMSE of 20%) under conditions of combined soil water stress and soil fertility stress, yield predictions were poor (RRMSE of 34%). Also Tsegay et al. (2012) noted, under conditions of non limiting soil fertility, that AquaCrop performs less well in the estimation of tef yield under water-stressed conditions. Further calibration of the effects of water stress on the harvest index of tef might be necessary in order to improve yield predictions under water-stressed conditions, both with and without soil fertility stress.

Notwithstanding its simplicity, the AquaCrop semi-quantitative approach performs as well as nutrient-balance-based models for the simulation of maize and wheat production under different levels of soil fertility stress and soil water stress. In evaluating simulations of wheat and maize production under different water and nitrogen treatments, Fang et al. (2008) found RRMSE values of 12% for biomass and 12-15% for yield with the CERES model, whereas Brisson et al. (2002) reported RRMSE values of 2-3% for biomass but 16-24% for yield using the STICS model; and Stöckle et al. (2003) reported RRMSE values between 8 and 14% for biomass and 8 and 32% for yield simulated with the CropSyst model. The APSIM model has been evaluated on a number of occasions for the simulation of more challenging situations such as, for example, the response of a crop to phosphorus or organic fertilizer. Micheni et al. (2004) and Kinyangi et al. (2004) obtained R^2 values of between 0.75 and 0.88 for the simulation of maize biomass production grown with organic fertilizer. Evaluating the simulation of maize production under different phosphorus and nitrogen supply levels, Fosu-Mensah et al. (2012) found RRMSE values of about 15% for yield and R^2 values for biomass of between 0.89 and 0.91 (corresponding to RMSE values of 0.661-0.780 t/ha). Finally, Delve et al. (2009), who studied the performance of maize grown under different phosphorus sources (manure versus fertilizer) and treatments (rate and frequency of application), found R^2 values of 0.83-0.88 for biomass (corresponding to RRSME values of at least 26%) and of 0.74-0.81 for yield. For maize and wheat, the performance statistics found in this study (Table 3.4) are clearly within the range of statistics reported for studies with nutrient-balance-based models. For tef and quinoa, the performance of the model cannot be compared to the performance of other crop models, since AquaCrop is currently the only crop model that has been calibrated to simulate crop production for these under-utilized crops (Geerts et al., 2009a; Tsegay et al., 2012).

It should also be noted that the present study evaluated the performance of AquaCrop's fertility response algorithms against observations that were obtained from on-farm experiments in relatively small plots. As such, problems such as lodging of the crop, damage to some of the plots, (partial) loss of samples due to technical problems and transport, and a limited sample size during the growing season could not be avoided. This inevitably led to deviations among replicates that were sometimes substantial, and this led to large standard deviations in the graphs presented. It can be expected that similar experiments conducted in a controlled environment of an experimental research station would yield an even better match between the observed and simulated values for soil water balance, canopy development, biomass production and yield.

3.4.2 Input and calibration requirements

The semi-quantitative approach of AquaCrop requires the user to specify the soil fertility level, expressed as the relative biomass (B_{rel}) that can be expected in a fertility stressed field compared to that for a reference field in non-water-stressed conditions. The B_{rel} can readily be obtained from farmers, from experimental fields or from agricultural statistics relating to local crop production. The ease with which this input can be obtained makes the semi-quantitative AquaCrop approach user-friendly and accessible to users worldwide. Moreover, the approach integrates the effects of various soil nutrients (and not merely nitrogen) and mineralization processes without a requirement for vast amounts of input data, for initialization of the soil nutrient conditions, or for elaborate parametrization.

The AquaCrop model is applicable to different crops and environmental conditions, but the crop response to soil fertility stress is crop- and case-specific and consequently the model requires calibration in each case. The necessity for a case-specific calibration diminishes the practicability of the model for analyses on a large spatial scale, but in this respect AquaCrop is no different from models that make use of a nutrient-balance approach, which also need site-specific information (Gabrielle et al., 2002; Matthews, 2002). Indeed, when crop production is being assessed over large areas, not only may various crops be being grown, but also the management, and the soil and nutrient conditions, may vary between different fields. Since each type of nutrient limitation affects canopy cover development and biomass in a different way, the crop response to soil fertility stress may differ amongst fields, even when the same crop is being grown. For example, a crop grown in a field where nitrogen is the most limiting nutrient will respond to the local soil fertility stress in a completely different way from a crop grown in a field where potassium is the most limiting nutrient.

Fortunately, as this research shows, when simulations are run for different fields within the same area, in which the constraints on crop growth are similar, the calibrated crop response to soil fertility stress is quite robust. In the present study, for example, the response of tef to soil fertility stress was calibrated for one of the experimental sites (Dejen), but the model also performed well in simulating crop development and production at the other experimental site (Maiquiha). In another assessment using AquaCrop in Ethiopia, in which the barley yield gap was investigated at the district level, it was demonstrated that after calibrating the response of barley to soil fertility stress for one experimental site, AquaCrop could estimate with acceptable accuracy (R^2 of 0.84 for B and

0.87 for Y, RMSE 0.82 t/ha for B and 0.23 t/ha for Y) barley biomass and yield under soil fertility stress for other farmers' fields within the same district (Abrha, 2013). A case-or field-specific calibration should therefore be considered only if large soil, nutrient or management differences occur within the same area.

Clearly, crop- and case-specific calibration results in extra work, but the effort involved is limited. First of all, the calibration procedure for the model is automated and requires few input parameters that are easily obtainable. The required information for canopy cover development (CC_x and canopy cover decline) in a 'soil fertility stressed' calibration field can be obtained by means of visual estimates in the field or from digital photographs, and can be specified as an input by selecting a class ranging from 'very strong reduction' to 'close to reference, or small reduction'. Secondly, the calibration of the crop response to soil fertility stress is important mainly for a correct simulation of the soil water balance and canopy development, and less important for the assessment of crop biomass production under soil fertility stress, for which B_{rel} already gives an indication of the reduction of biomass (and consequently yield) due to soil fertility stress. The automated calibration aims to determine the relative contributions of all four effects (reduced CC expansion, reduction of CC_x, early CC decline, reduction of wp*) to the overall effect of soil fertility on biomass production. This calibration step was introduced because the soil water content can be simulated more accurately by making a distinction between the soil fertility effect on wp*, which does not directly affect the soil water balance and the three soil fertility effects on canopy cover development (reduced CC expansion, reduction of CC_x, early CC decline), which do affect the soil water balance through their effect on transpiration. A reliable simulation of the soil water balance is of course indispensable for an accurate simulation of crop production (Aggarwal, 1995; Eitzinger et al., 2004), certainly in the AquaCrop model, which is based wholly on a water-driven growth module. Moreover, it allows the user to simulate the combined effect of soil fertility and water stress, which is an important strength of the AquaCrop model. Although very important for the simulation of the soil water balance, the calibration step is less important for the simulation of biomass production under soil fertility stress. Indeed, an indication of the local B_{rel} is sufficient to calculate the reduction of biomass (and consequently yield) that is due to soil fertility stress. For this reason, the calibration of the crop response to soil fertility should be seen more as a fine-tuning and estimation of the effect of soil fertility stress on canopy development and the soil water balance, rather than as a procedure that requires exact numbers and detailed information. This has also been illustrated by experimental data from Bolivia. Although data on canopy cover development were sparsely available, calibration nevertheless resulted in good predictions of biomass and yield.

3.4.3 Application of the model

After carrying out the calibration of the crop response to soil fertility stress, a user can apply the AquaCrop model to evaluate various soil fertility management strategies for the local environmental conditions, with respect to their effects on yield and crop water productivity. When conducted under different climatic conditions (wet versus normal or dry years), such a scenario analysis can help to develop best-practice guidelines for farmers, taking into account the interactions between variable climatic conditions and soil fertility management (Chapter 5). Moreover, the AquaCrop model accounts for the effect of elevated atmospheric CO_2 concentration on crop production (Subsection 2.5.3), so that fertility management strategies can be evaluated not just for historical or current climatic conditions, but for future climate scenarios as well.

On account of the lack of a dynamic soil nutrient-balance, however, the AquaCrop model is less suited to producing fertilizer recommendations. The model can reveal which soil fertility level optimizes crop (water) productivity, but it does not provide information on the amounts of nutrients that are required to attain this level of production. To establish fertilizer recommendations, the soil fertility level (B_{rel}) still has to be converted to the amounts of nutrients that are required to achieve the corresponding crop yield and consequently to the fertilizer dose that is required. Oyarmoi (2013) proposed that the concept of Nitrogen Agronomic Efficiency (NAE) could be used to define the nitrogen fertilizer dose based on the AquaCrop B_{rel}. However, further research based on experimental data is needed in order to evaluate the performance of this NAE-based approach.

Finally, it is clear that after analysing the agronomic benefits of different field management strategies using AquaCrop, a socio-economic analysis is indispensable. Following the examples of García-Vila et al. (2009), García-Vila and Fereres (2012) and Cusicanqui et al. (2013), who optimized irrigation management both from an agronomic and an economic point of view, it is clear that AquaCrop simulation results can be coupled to economic models so as to analyse the effect of the soil fertility management strategies on labour requirements and farmers' profits.

3.5 Conclusion

AquaCrop simulates the effect of soil fertility stress on crop production by making use of the relative biomass that can be expected in a fertility stressed field compared to a reference field, as a measure for soil fertility stress. This semi-quantitative approach requires few input parameters, which are easily obtainable, and integrates the effects of various soil nutrients and mineralization processes. In the present study, it is shown that in spite of its simplicity, the procedure results in an accurate simulation of the soil water balance, crop development, biomass production and yield for several soil fertility levels, and for various crops at different locations, following case-specific calibration. Moreover, the procedure shows potential for application in dry conditions, because the model performed well under conditions of combined soil water stress and soil fertility stress. With its integrated soil fertility module, the AquaCrop model is a useful tool with which to investigate the impact of soil fertility management on local crop production for different crops, and with which to develop best-practice guidelines in locations where the acquisition of detailed field information on soil nutrients is difficult. Furthermore, the model can be used to explore existing yield gaps and their major causes, i.e. water stress, soil fertility stress and combinations of both.

Chapter 4

Development and evaluation of the AquaCrop weed management procedure

This chapter is based on:
Van Gaelen, H, Delbecque, N, Abrha, B, Tsegay, A, and Raes, D (2016a). Simulation of crop production in weed-infested fields for data-scarce regions. *The Journal of Agricultural Science*, 154 (6), 1026–1039. DOI: http://dx.doi.org/10.1017/S0021859615000982

4.1 Introduction

Nowadays, studies on agricultural productivity rely increasingly on simulation models. Being more cost- and time-efficient, crop models offer an attractive supplement to field experiments. Crop models are not only used to estimate potential yield levels and investigate causes of yield gaps, but also to evaluate management strategies that can boost crop productivity and water use efficiency. Initially, most crop models were developed to simulate crop production at field scale for historical time series. However, model application has evolved towards large scale studies as well as prediction of future crop productivity.

While most crop models consider yield-limiting factors such as water stress and nutrient deficiencies, biotic factors such as weeds are often neglected. Notwithstanding, considerable yield losses due to weeds are not only faced by smallholder farmers in developing countries (FAO, 2009), but also occur in large scale intensive cropping systems in developed countries (Swanton et al., 1993; Pimentel et al., 2000; Milberg and Hallgren, 2004). In addition, weeds transpire water and thereby reduce water availability to the crop. This unproductive water consumption is critical in drought-prone regions, where optimizing crop water productivity is a prerequisite for sustainable crop production.

To include the effect of weed infestation in simulation studies, one could apply empirical equations that predict crop yield losses based on variables such as weed density (Cousens, 1985), relative time of weed emergence (Cousens et al., 1987), relative leaf area (Kropff et al., 1995), and relative leaf cover of the weeds (Lotz et al., 1994). However, these empirical equations entirely rely on locally calibrated parameters, which hinder extrapolation to other weed species, crop species, locations, environmental conditions, and management practices (Kropff et al., 1992; Murphy et al., 2002). Also, process-oriented, mechanistic simulation models such as ALMANAC (Kiniry et al., 1992), APSIM (Keating et al., 2003), CROPSIM (Chikoye et al., 1996) and INTERCOM (Kropff and van Laar, 1993) have been developed or extended to study crop-weed interactions. However, high requirements for input data, parameter calibration and validation impede efficient application of these models for a wide range of environmental conditions and cropping systems (Weaver, 1996). Particularly in data-scarce regions, application of existing mechanistic simulation models is impractical.

The AquaCrop crop water productivity model (Hsiao et al., 2009; Steduto et al., 2009; Raes et al., 2009; Vanuytrecht et al., 2014a) was developed by the Food and Agriculture Organization of the United Nations (FAO) to estimate yield for herbaceous crops cultivated under various environmental conditions and management practices. Although the model is mechanistic by nature, simulated processes in the crop-soil system are largely simplified. Notwithstanding these simplifications, AquaCrop provides accurate productivity estimates based on a limited number of easily obtainable input variables and parameters. This makes the model practical to apply in data-scarce regions, as well as for studies on a regional scale (Lorite et al., 2013; Kim and Kaluarachchi, 2015). AquaCrop has been applied to assess irrigation and soil fertility management strategies (Geerts et al., 2009b, 2010; Shrestha et al., 2013b,a; Tsegay et al., 2015), but a weed management module has been missing.

That is why, a weed management module was developed for implementation in AquaCrop, pursuing a good balance between model accuracy and input requirements. This chapter discusses the newly developed AquaCrop calculation algorithms for crop yield simulation in weed-infested fields. Moreover, the performance of the AquaCrop model to simulate the soil water content, canopy cover development and crop production in weed-infested fields is evaluated for two different grain crops grown in various environmental and agronomic conditions.

4.2 Methodology

4.2.1 The AquaCrop model for weed-infested conditions

AquaCrop simulates crop productivity using a four-step process as discussed in Section 2.3. First, green crop canopy cover (CC) is simulated. In a second step, crop transpiration (Tr) is simulated considering reference evapotranspiration (ET_0) and the simulated canopy cover. Next, crop transpiration is converted into dry above-ground biomass production (B). In a final step, crop biomass is converted to crop yield (Y) by means of the harvest index (hi). Crop yield per unit of water evapotranspired (ET) is given by the ET crop water productivity (WP_{ET}). During this four-step simulation process, the model accounts for the effect of various abiotic stresses, including water stress, temperature stress, soil salinity stress and soil fertility stress (Section 2.5).

When weed stress is considered, AquaCrop directly simulates crop canopy development as it is observed in a weed-infested field (CC_W, Figure 4.1). In addition, AquaCrop simulates canopy development of the crop-weed mixture (CC_{TOT}, Figure 4.1), which will be referred to hereafter as ‘total vegetation’. Simulation of total vegetation canopy cover is crucial since the denser canopy in weed-infested fields affects soil evaporation, transpiration and consequently water availability in the root zone and crop water productivity. In AquaCrop, total vegetation is represented by a theoretical crop with denser canopy cover, but otherwise identical characteristics to the crop growing in a weed-free field (CC_{WF}, Figure 4.1). Hence, crop characteristics such as phenology, rooting depth, growing cycle length and sensitivity to abiotic stresses are also applicable to the total vegetation. The denser canopy is reflected by both a higher initial (CC_0) and maximum canopy cover (CC_x). Due to this denser canopy and assumption of equal growing cycle length, the canopy decline rate of the total vegetation is also higher compared to the decline rate of the crop.

Simulation of both the total vegetation and crop canopy cover in weed-infested fields is completely determined by two user-specified inputs: (i) the weed infestation level or amount of weeds and (ii) the weed-induced increase of total canopy cover.

The weed infestation level is quantified by means of the relative leaf cover of weeds (RC, Equation 4.1) as defined by Lotz et al. (1994).

$$RC = \frac{WC}{CC_{TOT}} = \frac{WC}{WC + CC_W} \tag{4.1}$$

where RC is the relative leaf cover of weeds ($\mathrm{m}^2/\mathrm{m}^2$), WC is the area covered by weeds per unit ground area ($\mathrm{m}^2/\mathrm{m}^2$), CC_W is the area covered by the crop per unit ground area in a weed-infested field ($\mathrm{m}^2/\mathrm{m}^2$), and CC_{TOT} is the

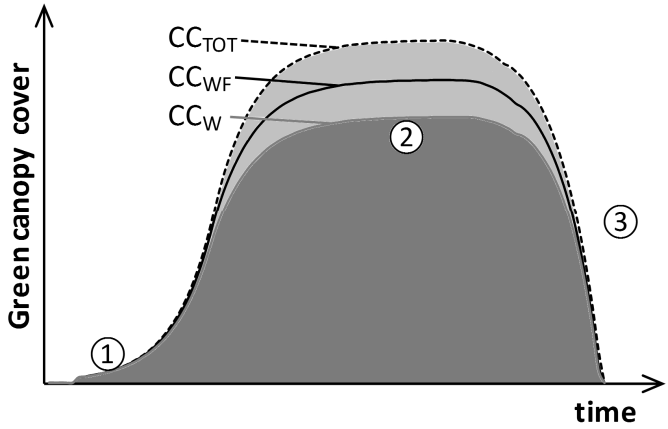


Figure 4.1: Weed infestation affects the simulated (1) initial canopy cover, (2) maximum canopy cover, and (3) canopy decline rate. As weeds (light grey) take up empty space or suppress the crop (dark grey), the crop canopy cover in weed-infested conditions (CC_W) is lower compared to weed-free conditions (CC_{WF}). Moreover, the canopy cover of the total vegetation (CC_{TOT}) is higher and has a faster decline compared to the crop canopy cover in weed-free conditions (CC_{WF}).

area covered by the total vegetation (crop-weed mixture) per unit ground area (m^2/m^2).

Relative weed cover is a multi-species canopy characteristic that varies during the growing season. Since the weed's share in leaf area at time of canopy closure is regarded as a good indicator of crop-weed competition (Kropff and Spitters, 1991), AquaCrop requires input of RC observed at the time maximum crop canopy cover is reached.

The weed-induced increase of total canopy cover ($\mathrm{f_{weed}}$) is defined as:

$$f_{weed} = \frac{CC_{x,TOT}}{CC_{x,WF}} \tag{4.2}$$

where $\mathrm{f_{weed}}$ is the weed-induced increase of total canopy cover (-), $CC_{x,TOT}$ is the maximum total vegetation canopy cover (m^2/m^2) and $CC_{x,WF}$ is the maximum crop canopy cover in weed-free conditions (m^2/m^2).

A large $\mathrm{f_{weed}}$ value indicates that weeds predominantly fill any empty gaps in the crop canopy cover, which results in a strong increase of the total canopy cover as compared to weed-free conditions. A small $\mathrm{f_{weed}}$ value, on the other hand, indicates that weeds predominantly suppress crop growth by 'stealing' light. This results in a small increase in total canopy cover. Hence, for a certain weed infestation level (RC), differences in weed competitive abilities can result in different total vegetation canopy covers, and consequently different f_{weed} values. The AquaCrop user defines f_{weed} either directly or by specifying $CC_{x,TOT}$ for the selected weed infestation level and optimal growing conditions (no fertility, water or salinity stress). In addition, AquaCrop can determine f_{weed} based on a user-specified canopy expansion factor (f_{shape}). This f_{shape} factor fixes the relation between the observed weed infestation level (RC) and the maximum total vegetation canopy cover ($CC_{x,TOT}$) for optimal growing conditions (Figure 4.2), and consequently represents the competitive ability of weeds to compete with the crop for light. A negative f_{shape} value points out that the crop is more competitive than the weeds, whereas a positive f_{shape} value indicates that the weeds are more competitive than the crop.

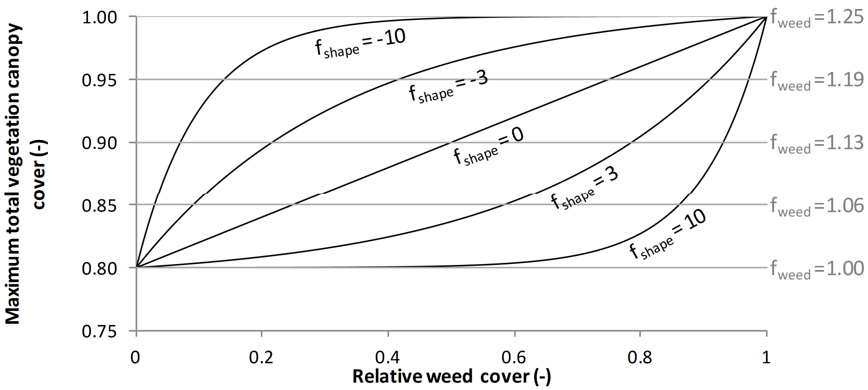


Figure 4.2: Relationship between maximum total vegetation canopy cover ($CC_{x,TOT}$) and relative cover of weeds (RC) is determined by the canopy expansion factor (f_{shape}). This relationship can be used to derive the weed-induced increase of total canopy cover (f_{weed}) for a given weed infestation level. This example presents a crop with a maximum canopy cover ($CC_{x,WF}$) of 0.8 in weed-free conditions.

An AquaCrop simulation for weed-infested conditions starts by simulating total vegetation canopy cover (CC_{TOT}) by multiplying the crop canopy cover under weed-free conditions ($CC_{x,WF}$) with f_{weed}. Next, CC_{TOT} is corrected for water, soil fertility or soil salinity stress using the stress thresholds calibrated for the crop. Thereby it is assumed that weeds are equally as sensitive to those stresses than the crop. Subsequently, the crop canopy cover for weed-infested conditions (CC_W) is derived from CC_{TOT} based on RC (Equation 4.1). Finally, simulation of CC_W enables simulation of crop transpiration, crop biomass, crop yield and crop water productivity in weed-infested fields using the standard AquaCrop procedure (Equation 2.1 to Equation 2.4).

Since weeds take up water and affect the soil water balance, AquaCrop calculates the soil water content in the root zone (SWC_r) of a weed-infested field considering the total vegetation canopy cover. Evaporation and transpiration of the total vegetation are simulated considering the denser canopy of weed-infested versus weed-free fields (CC_{TOT} versus CC_{WF}). The simulated soil water content is used to correct the simulated total vegetation canopy cover, crop transpiration and yield formation in a weed-infested field for water stress. It should be noted that increased water stress is the only mechanism through which weeds affect the harvest index in AquaCrop. An additional adjustment to the harvest index for weeds is not considered. Furthermore, weeds increase nutrient stress by ‘stealing’ crop nutrients. For that reason, the soil fertility level is adapted during simulation. In addition, a weed-induced increase of total canopy cover is no longer considered (f_{weed} is 1), since low soil fertility restricts total canopy cover development to the level that can be reached in weed-free conditions ($CC_{x,TOT}$ equals $CC_{x,WF}$).

4.2.2 Field experiments

The AquaCrop weed management algorithms were tested against two sets of experimental data (Table 4.1). The first set comprised data of four experiments conducted with barley (*Hordeum vulgare* L.) in the drought-prone, degraded highlands of Tigray in northern Ethiopia. The second set consisted of data from a field experiment with winter wheat (*Triticum aestivum* L.) conducted in semi-arid Wagga Wagga, Australia.

All experiments were set up with a split-plot design in which water treatment was the main factor and the weed treatment the sub-factor (Table 4.1). In S1 water treatments, crop development or production were affected by water stress, while crops did not suffer water stress in S0 treatments. Occurrence of water stress was caused by insufficient rainfall, inadequate irrigation, or the presence of a rainshelter. Since observed differences between water treatments were not significant for barley in all four experiments (Abrha, 2013), only one water treatment was retained for the current study (Table 4.1). In Dejen and Maiquiha, naturally occurring weeds were retained and weed treatments consisted of different hand weeding frequencies: no weeding, one time weeding at 21 days after emergence (only in 2009) and frequent weeding (at least three times). The majority of weed species were broad-leaved (e.g. *Scorpiurus muricatus*), but grasses (e.g. *Avena* sp., *Digitaria* sp.) and sedges (e.g. *Cyperus* sp.) were also present. In Mekelle, wild oat (*Avena fatua* L.) was sown together with barley at a proportion of 0%, 5%, 20% and 50% of the total amount of seeds. In Wagga Wagga, ryegrass (*Lolium rigidum* Gaud.) was sown aiming at a weed density of 250 plants/m^2. At all experimental sites, the plots were kept free from pests, diseases and undesired weeds throughout the growing season. Moreover, all plots were kept at optimal fertility to ensure that neither crops nor weeds would suffer from nutrient stress. During the growing season observations of local daily weather, soil characteristics, irrigation and soil fertility management, soil water content, crop phenology, crop and weed canopy (leaf area index (LAI) or green canopy cover), dry above-ground crop biomass and crop yield, were recorded. Observations of the second data set were retrieved from the paper by Deen et al. (2003) or shared by those authors. Unfortunately, not all data could be retrieved; some observations of the weed-infested plots were missing (e.g. yield and soil water content) or observations were limited to average values without records of the deviation between replications. More detailed information on the experimental set-up and data collection is described by Deen et al. (2003) for winter wheat, and Abrha et al. (2012) and Abrha (2013) for barley.

Table 4.1: Experimental sites, set-up and environmental conditions of the five experiments. Water treatments consist of absence (S0) or presence (S1) of water stress. The seasonal aridity index (AI) represent the ratio of total rainfall to reference evapotranspiration (ET_0) during the growing season.

	Dataset 1				**Dataset 2**
Experimental site	Dejen	Dejen	Maiquiha	Mekelle	Wagga Wagga
Country	Ethiopia	Ethiopia	Ethiopia	Ethiopia	Australia
Coordinates	13°20'N, 39°22'E	13°20'N, 39°22'E	13°48'N, 39°27'E	13°28'N, 39°29'E	35°10'S, 147°28'E
Altitude (m a.s.l.)	2128	2128	2078	2212	200
Experimental set-up					
Location	Farmer training centre	Farmer's field	Farmer's field	Research station	Research station
Season	2009	2010	2009	2010	1998
Sowing date	10/07/2009	13/07/2010	15/07/2009	15/07/2010	18/05/1998
Replications	3	3	3	3	5
Crop	Barley	Barley	Barley	Barley	Winter wheat
Weed species	Natural mix	Natural mix	Natural mix	Wild oat	Ryegrass
Water treatment(s)	S0	S0	S1	S0	S0, S1
Weed treatments	Weeding frequency: 0, 1, $\geq$3 times/season	Weeding frequency: 0, $\geq$3 times/season	Weeding frequency: 0, 1, $\geq$3 times/season	Weed seed proportion: 0, 5, 20, 50%	Weed density: 0, 250 plants/m^2
Environmental conditions					
Soil type	Luvisol	Luvisol	Leptosol	Cambisol	Red-brown earth soil
Soil texture	Sandy loam to silt loam	Loam to silt loam	Silt loam	Sandy (clay) loam	Loam, silty clay
Seasonal rainfall (mm)	301	443	239	552	420 (S0) and 122 (S1)*
Seasonal ET_0 (mm)	324	280	367	285	353
Seasonal AI (mm/mm)	0.93	1.58	0.65	1.94	1.19 (S0) and 0.35 (S1)*

* Seasonal rainfall was affected by the presence of a rain shelter in the S1 water treatment.

4.2.3 Model input

Observations of local climatic data, irrigation practices, soil characteristics and initial soil water content were used as inputs in a test version of AquaCrop 5.0 (AquaCrop 5.0*). Simulations were conducted assuming non limiting soil fertility for all plots. Default crop parameters (Table A.3) were used as a starting point; thereafter non-conservative crop parameters were adjusted to match the characteristics of the local cultivar and environment (Table 4.2). Crop development stages were specified in growing degree days (GDD) to enable temperature dependent crop canopy development. Conservative crop parameters, which by definition are independent of cultivar, management and geographical location, were kept default, except for wheat. Since AquaCrop does not consider typical processes for winter crops such as vernalization, dormancy and cold acclimation, simulation of winter wheat development required adaptation of some conservative crop parameters (Table 4.2) following the example of Vanuytrecht (2013).

Table 4.2: Key crop parameters for barley and wheat grown at the experimental sites. Values that were changed from the default are presented in bold. * indicates the values for Mekelle.

			Barley	**Wheat**
Non-conservative parameters				
Initial canopy cover	CC_0	%	2.70/**2.96***	**1.95**
Maximum canopy cover	CC_x	%	80/**88***	**88**
Time to emergence	eme	GDD	98	**80**
Time to start senescence	sen	GDD	924	**710**
Total length of crop cycle	mat	GDD	1296	**1401**
Maximum effective rooting depth	rtx	m	1.3	**1.2**
Conservative parameters				
Canopy growth coefficient	cgc	%/GDD	0.9	**1.115**
Canopy decline coefficient	cdc	%/GDD	0.6	0.400
Base temperature	tb	°C	2	**4**
Upper temperature	tup	°C	28	26
Minimum growing degrees required for full biomass production	stbio	°C/d	14	**10**
Normalized biomass water productivity	wp*	g/m^2	15.0	**18.5**
Reference harvest index	hio	%	33	48

Weed management inputs (RC and $\mathrm{f_{weed}}$), listed in Table 4.3, were determined applying Equation 4.1 and 4.2 to available CC_{WF}, CC_W and WC observations of well-watered plots at time of maximum crop canopy cover. For wheat experiments, LAI values were first converted to CC values using Equation 4.3 (Kropff and van Laar, 1993) with a light extinction coefficient (l) of 0.6 and 0.5 for wheat and ryegrass respectively (Lantinga et al., 1999; Acevedo et al., 2002).

$$CC = 1 - exp\left(\sum_{i=1}^{n} l_i \cdot LAI_i\right) \tag{4.3}$$

where CC is the green canopy cover (m^2/m^2), l_i is the light extinction coefficient (-), and LAI_i the leaf area index (m^2/m^2) of species i as observed in a field with n species.

Table 4.3: Weed treatments with selected AquaCrop weed management input: relative weed cover (RC) and weed-induced total canopy cover increase ($\mathrm{f_{weed}}$) with corresponding canopy expansion factor ($\mathrm{f_{shape}}$). Water treatments consist of absence (S0) or presence (S1) of water stress.

Experiment	**Water treatment**	**Weed treatment**	RC (%)	$\mathbf{f_{shape}}$ (-)	$\mathbf{f_{weed}}$ (-)
Dejen, 2009	S0	Weeding frequency			
		≥3 times/season	0	-	-
		1 times/season	15	1	1.02
		0 times/season	50	1	1.10
Dejen, 2010	S0	Weeding frequency			
		≥3 times/season	0	-	-
		0 times/season	13	-5.5	1.13
Maiquiha, 2009	S1	Weeding frequency			
		≥3 times/season	0	-	-
		1 times/season	14	-1	1.05
		0 times/season	30	-1	1.10
Mekelle, 2010	S0	Weed seed proportion			
		0%	0	-	-
		5%	8	10	1.00
		20%	23	10	1.00
		50%	49	10	1.00
Wagga Wagga, 1998	S0	Weed density			
		0 plants/m^2	0	-	-
		250 plants/m^2	20	-10	1.12
	S1	0 plants/m^2	0	-	-
		250 plants/m^2	15	-10	1.11

Since weed species were similar for all weed treatments of the same experiment, a single canopy expansion factor (f_{shape}) was selected for all treatments. The f_{shape} value was selected so that the f_{weed} values corresponding to this f_{shape} value for each *RC* level (see Equation 4.2) approached the observed f_{weed} values well. Moreover, water availability in wheat plots affected the amount of weeds at time of canopy closure so that different *RC* values were selected for both water treatments.

4.2.4 Model performance evaluation

The AquaCrop model was evaluated for its performance to simulate soil water content in the root zone, crop canopy cover, total vegetation canopy cover, crop biomass and crop yield both for weed-free and weed-infested conditions. Thereby observations of all experimental sites and water treatment, listed in Table 4.1, were included. Performance was assessed using graphical displays (plots of simulated versus observed values) and the four statistical indicators presented in Box 2.1: R^2, RRMSE, EF and RME. Model performance was qualified based on RRMSE values following Jamieson et al. (1991).

4.3 Results

Two examples, presented in Figure 4.3, illustrate how AquaCrop simulates the effect of weed infestation on barley canopy and biomass development. The total vegetation canopy cover increased due to presence of weeds, while crop canopy cover reduced. As a consequence, less biomass was produced. Even though both experiments had a similar weed infestation level of about 50% (Table 4.3), the simulated weed-induced increase of total canopy cover was strong in the experiment of Dejen (2009), while it was negligible in Mekelle (2010). This was the results of selecting a different f_{weed} value (Table 4.3). Since the effect of weeds on crop canopy cover differed between both experiments, the weed-induced reduction in biomass differed as well. The simulated decrease of crop final biomass due to a 50% *RC* was about 43% for Mekelle, but only 39% for Dejen. Also field observations indicated that due to the high crop sowing density in Mekelle there was almost no empty space in the canopy for weeds to occupy. While in Dejen only some weeds competed with the crop for light, all the weeds in Mekelle suppressed the crop by outcompeting it for light, thereby causing larger reduction in biomass.

The goodness-of-fit statistics (Table 4.4) present the performance of AquaCrop to simulate different crop variables of both weed-free and weed-infested barley and wheat plots including all experimental sites and water treatments.

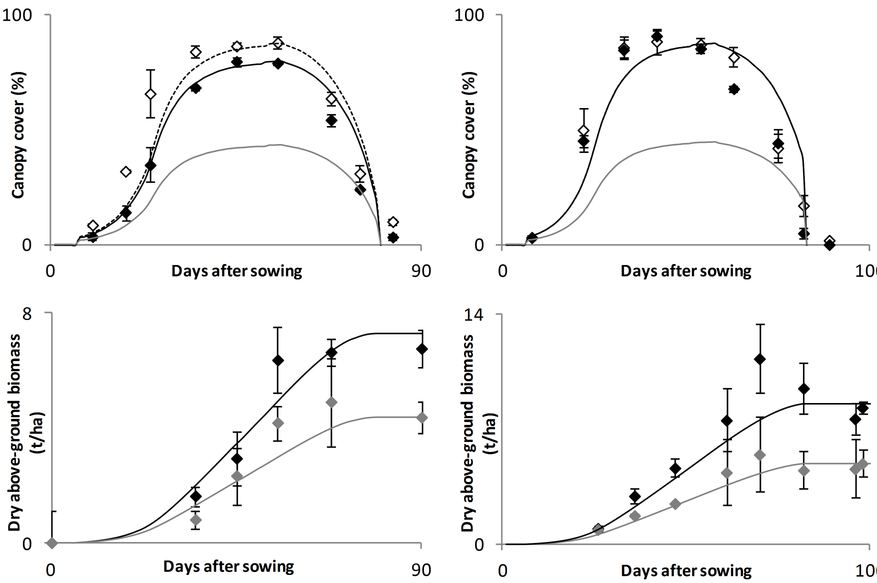


Figure 4.3: Simulated (lines) and observed (symbols) canopy cover (top) and dry above-ground biomass (bottom) in well-watered barley plots in Dejen 2009 (left) and Mekelle 2010 (right). Crop canopy cover and biomass are affected by the weed infestation level: weed-free (black) and weed-infested with a relative weed cover of about 50% (grey). The dashed line and open symbol present the total vegetation canopy cover in weed-infested conditions. Error bars indicate ± standard deviation for three replications.

AquaCrop made fair predictions of barley canopy cover development and biomass build-up during the growing season, as shown by the RRMSE values of between 21 to 24% (Table 4.4). Regardless of the fair biomass predictions during the growing season, biomass at maturity was the most accurately predicted crop variable for both weed treatments (RRMSE values of 5-6 %). Moreover, AquaCrop made very good predictions of soil water content in the root zone (RRMSE of about 12-13%), despite only fair predictions of canopy cover and consequently transpiration. Furthermore, Table 4.4 illustrates that simulations were slightly less accurate for weed-infested barley plots compared to weed-free conditions. RRMSE values of weed-infested treatments were only 1.5-2.5% higher than weed-free treatments for soil water content and biomass. Predictions of barley biomass at maturity were even better than for weed-free conditions. Although final biomass was predicted excellent for all weed treatments, model performance decreased for grain yield depending on the weed treatment; barley yield predictions were very good for weed-free conditions (RRMSE of 12%), but only fair for weed-infested conditions (RRMSE of 25%). Figure 4.4 shows that yield was overestimated for all weed treatments, while biomass was predicted accurately. This indicates overestimation of the harvest index.

Table 4.4: Relative root-mean-square error (RRMSE), Nash-Sutcliffe model efficiency (EF) and coefficient of determination (R^2) for n number of observations of average soil water content in the root zone (SWC_r), crop canopy cover in weed-free conditions (CC_{WF}) or weed-infested conditions (CC_W), total vegetation canopy cover (CC_{TOT}), dry above-ground crop biomass (B) during the growing season and at phenological maturity, and crop yield in weed-free and weed-infested barley and wheat plots (all experimental sites and water treatments included). Dashes indicate that observations for performance assessment were unavailable.

	Weed-free				**Weed-infested**			
	n (-)	RRMSE (%)	EF (-)	R^2 (-)	n (-)	RRMSE (%)	EF (-)	R^2 (-)
Barley								
SWC_r	33	11.6	0.80	0.82	66	13.2	0.77	0.78
CC_{WF}	36	22.8	0.90	0.90	-	-	-	-
CC_{TOT}	-	-	-	-	73	22.3	0.90	0.90
B season	26	21.2	0.85	0.88	52	23.7	0.83	0.87
B maturity	4	6.5	0.87	0.90	8	5.3	0.95	0.95
Yield	4	11.5	0.67	0.88	8	25.3	0.18	0.85
Wheat								
SWC_r	32	4.5	0.68	0.77	-	-	-	-
CC_{WF} or CC_W	15	18.1	0.95	0.96	15	14.8	0.96	0.96
CC_{TOT}	-	-	-	-	15	20.7	0.92	0.93
B season	17	29.9	0.92	0.95	17	38.9	0.85	0.92

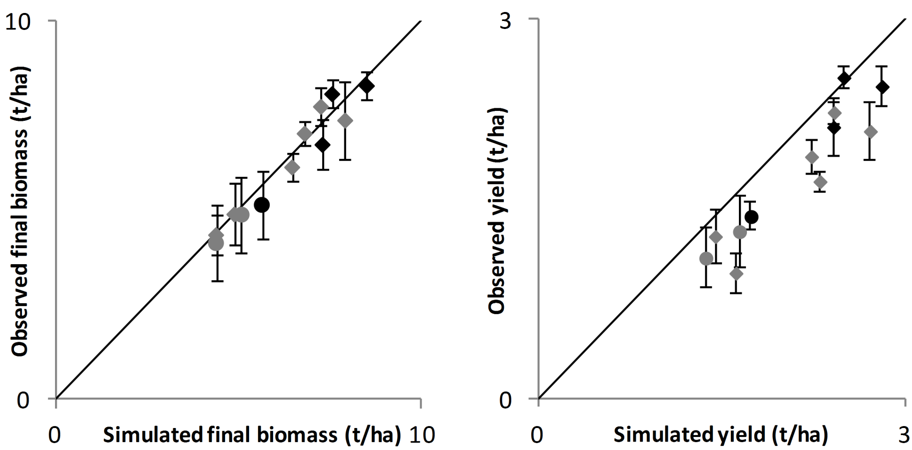


Figure 4.4: Observed versus simulated dry above-ground biomass at maturity (left) and dry grain yield (right) of barley grown in weed-free (black) and weed-infested (grey) plots with water stress (circle) or without water stress (diamond) at the three experimental sites in 2009 and 2010. Error bars indicate ± standard deviation for three replications.

Simulation of the soil water content in the root zone of weed-free wheat plots was excellent, as indicated by the small RRMSE value of 4.5% (Table 4.4). However, because soil water content simulations were less good for the S0 treatment, EF and R^2 values were rather low. Unfortunately, observations of soil water content were not available for weed-infested fields. Furthermore, AquaCrop performed good for simulations of crop and total vegetation canopy cover, with RRMSE values between 15 and 21%. In contrast, performance was poor for simulation of crop biomass during the season. Figure 4.5 illustrates that AquaCrop was not able to capture the slow biomass build-up during winter, even though conservative crop parameters were altered to match the characteristics of winter wheat (Table 4.2). Introduction of weeds further decreased model performance. In weed-infested conditions, RRMSE values were 3-9% higher than in weed-free conditions. In spite of AquaCrop's limitations to accurately simulate biomass development, biomass at maturity was predicted very accurately with relative model errors (RME) as small as 1 to -2%. For both water treatments, final biomass in weed-free plots was underestimated, but overestimated for weed-infested plots.

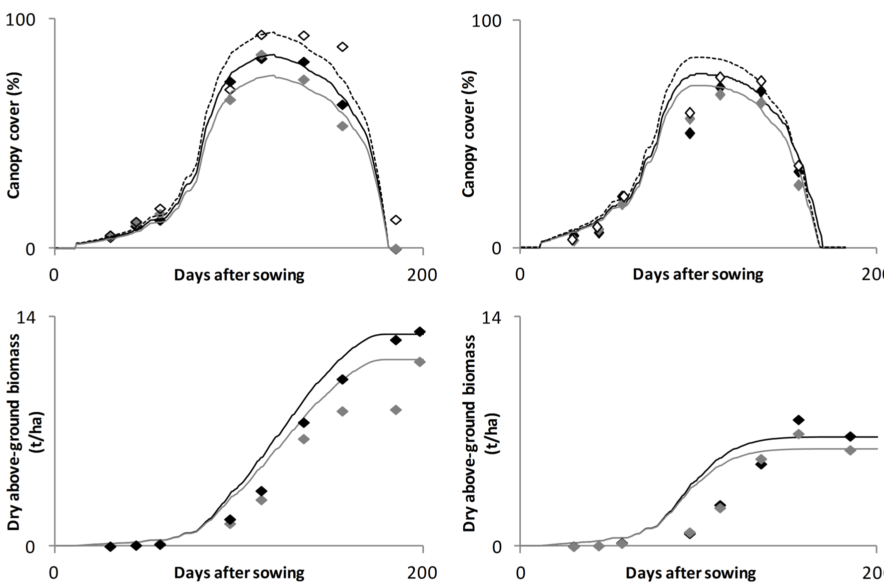


Figure 4.5: Simulated (lines) and observed (symbols) canopy cover (top) and dry above-ground biomass (bottom) in well-watered (left) and water-stressed (right) wheat plots in Wagga Wagga, 1998. Crop canopy cover and biomass are affected by the weed infestation level: weed-free (black) and weed-infested (grey) with a relative weed cover of about 20% for well-watered and 15% for water-stressed plots. The dashed line and open symbol present the total vegetation canopy cover in weed-infested conditions. Data points represent an average value over five replications. Error bars indicating the standard deviation were not available for the wheat dataset.

4.4 Discussion

4.4.1 Model approach

Data availability is a major bottleneck for application of existing crop-weed competition models. In contrast, AquaCrop requires limited input variables and parameters that can be easily obtained (Section 2.2). Simulation for weed-infested conditions requires only two additional inputs (RC and f_{weed}), which can be easily determined by analysing digital photographs or from remote sensing images (Lotz et al., 1994; Burgos-Artizzu et al., 2009). If such digital images are not available, one can also rely on visual estimates done in the field (Andújar et al., 2010). Since the two weed management inputs need to be specified for the weed mixture, knowledge of the exact weed species is not required. Moreover, this multiple-species approach is an important advantage, because competition by a single weed species is rarely encountered in farmers' fields.

AquaCrop relies completely on the input of relative weed cover to simulate partitioning of resources between crop and weeds. Light partitioning is by definition represented by RC. Water partitioning requires the total transpiration to be divided into crop and weed transpiration based on total vegetation canopy cover and crop canopy cover. Since the latter are related through RC, partitioning of water is clearly determined by RC. Also, nutrient partitioning requires the soil fertility stress level to be adapted based on RC. One could argue that such an RC based approach neglects the competitive ability of weeds versus crop to obtain light, water and nutrients. Also, differences in sensitivity to scarcity of these resources seem to be neglected. However, this is not true since f_{weed} incorporates the competitive ability of crop and weed to obtain light. In addition, RC serves as a proxy for competitive ability and sensitivity to water and soil fertility stress. Also, Aldrich (1987) found light competition to be representative for total competition, since canopy size and structure is the result of competition for light, water and nutrients, as well as allelopathic interactions. Moreover, photosynthesis is not just involved in light competition, but also provides the energy for uptake of nutrients and water.

Furthermore, AquaCrop uses a static approach regarding weed infestation, as it uses a constant value of RC at time of maximum canopy cover to define the effect of weeds on crop canopy cover during the whole growing season. Such a static approach neglects the dynamics of weed cover, which can increase or decrease during the growing season depending on the competitive ability of crop versus weed. However, the absolute error made with this static approach is negligible at the beginning of the growing season, because canopy cover is still very small and little biomass is produced during the canopy expansion phase.

In contrast, the error could be larger in mid-season, when crop canopy cover is large and most biomass is produced. Although the current study proved that good model results can be obtained with the static approach, future research should indicate whether *RC* dynamics in mid-season have a large impact on model results and should be incorporated in the model.

Finally, it should be noted that AquaCrop's representation of the crop-weed vegetation as a single theoretical crop with the same growing cycle as the weed-free crop neglects possible differences between the crops' and weeds' growing cycles. Nevertheless, this simplification is valid both for late-emerging weeds, that cannot outgrow the crop, and for early-emerging weeds, which are removed during land preparation. Moreover, weeds with a life cycle similar to that of the crop will usually be the most successful competitors (Zimdahl, 2013) and consequently lead to major yield losses.

4.4.2 Model performance

AquaCrop performed well for simulation of barley growth and production. This indicates that the selected crop parameters and inputs were a good representation of the local environment and cropping system. As the default crop parameters had been calibrated and validated by Abrha et al. (2012) for the same local barley variety grown in weed-free conditions, this is no surprise. Overestimation of yield indicated incorrect simulation of the harvest index, especially in weed-infested plots. This could be due to inaccurate settings of the barley water stress thresholds, or because AquaCrop disregards any direct effect of weeds on grain formation. Field experiments show that weeds can reduce barley grain yield by lowering the number of ear bearing tillers, number of grains per ear, and 1000-kernel weight (Wilson and Peters, 1982; Morishita and Thill, 1988). Introducing an *RC*-dependent stress coefficient that affects the harvest index, could improve model simulations. However, this would also lead to extra parameter uncertainty in the model.

Model performance to simulate wheat production was less good compared to barley, in particular for simulation of biomass during the growing season. It is expected that introduction of an extra stress coefficient to represent slow crop development because of low winter temperatures, as previously proposed by Vanuytrecht (2013), would significantly improve AquaCrop's performance for both weed-free and weed-infested winter wheat simulations. Despite the poor in-season biomass predictions, AquaCrop made excellent predictions of wheat biomass at maturity. In practice, final biomass, and not intermediate biomass, is most crucial to assess weed-induced yield losses.

Moreover, AquaCrop's performance for the wheat dataset was well within the performance range of four mechanistic crop-weed competition models

(ALMANAC, APSIM, CROPSIM, INTERCOM) that were tested with the same dataset by Deen et al. (2003)(Box 4.1). However, this model performance comparison should be interpreted with care, as the AquaCrop approach is very different from mechanistic crop-weed competition models. The latter predict both crop and weed growth, partitioning of resources between crop and weed, and the resulting crop yield loss due to weeds. AquaCrop, on the other hand, uses input of the observed effect of weeds on crop canopy cover at time of canopy closure to simulate the effect of weeds on the soil water balance and crop production.

Finally, it should be noted that because of the experimental set-up, the current study focused mainly on simulation of the outcome of crop-weed competition for light. Model performance for water competition was assessed based on the weed-infested, water-stressed treatments, which were only available for one of the barley experiments (Maiquiha 2009) and the wheat experiment. Although model performance proved promising for these experiments, additional research including different water stress levels, ranging between low and very severe water stress, could further reveal to what extent AquaCrop can accurately capture the effect of weeds on soil water content and crop water availability. Furthermore, competition for nutrients was not considered in this study, because the soil fertility level was optimal in all experiments. Therefore, further evaluation of AquaCrop for weed-infested, soil-fertility-stressed fields remains necessary.

4.4.3 Model application

Once properly calibrated to the local environment and cropping system, AquaCrop can be used to simulate crop growth, production and water productivity in weed-infested fields. Notwithstanding its simple approach, the new weed module is widely applicable. This was demonstrated by model evaluation for various experimental set-ups including different locations, soil types, climatic conditions, water treatments, crops, weed species and weed infestation levels. Furthermore, limited input and calibration requirements make AquaCrop applicable in data-scarce regions. If data are sparse, weed management inputs can even be specified in qualitative terms. A user can select one of the predefined *RC* classes, ranging between 'very poor' and 'perfect' weed management, or one of the predefined f_{weed} classes ranging between 'very weak' and 'very strong' weed-induced increase of total canopy cover.

Addition of weed infestation as a production- and water-limiting factor improves accuracy of yield predictions and yield gap analysis in weed-infested areas. Other potential model applications include investigation of tolerable weed infestation levels, as well as assessment of yield loss mitigation strategies such as changing sowing density or crop type. AquaCrop has the important advantage that weed infestation scenarios can be evaluated based on both simulated crop yield and crop water productivity. Assessing both these productivity indicators is vital in water-scarce regions, where management decisions should be made in view of limited water availability.

Even though potential applications are numerous, the AquaCrop approach has limitations. The model can only support strategic management decisions, and cannot be used for assessment of tactical decisions. For example, model simulations can provide information on tolerable weed infestation levels, but can optimize neither pesticide dose nor timing of weed control operations. Moreover, the model cannot provide additional insights into the competition mechanisms. This would require a more detailed, process-based approach as adopted by other mechanistic models. Finally, it is clear that AquaCrop can support weed management decisions only from an agronomic point of view. However, by linking AquaCrop to an economic model, weed management can be optimized accounting for factors including labour and time requirement of weed control operations, prices of herbicides and prices of crop products. An example was set by Dunan et al. (1994, 1999) who optimized weed management based on both agronomic and economic aspects. Moreover, the linkage of AquaCrop to economic models has been demonstrated by García-Vila et al. (2009), García-Vila and Fereres (2012) and Cusicanqui et al. (2013).

4.5 Conclusion

The AquaCrop approach to simulate crop production in weed-infested fields requires just two easily obtainable input variables: the relative leaf cover of weeds and weed-induced increase of total canopy cover. This makes the model applicable to all herbaceous crops grown in competition with any type or number of weeds. Despite its simple approach, AquaCrop performs good to simulate soil water content, crop development and crop production in weed-infested barley and wheat fields over a wide range of environmental and agronomic conditions. Further testing of the model remains necessary to assess model performance for weed-infested conditions combined with nutrient limitations or severe water stress. Because of its simple but accurate simulation procedure, wide applicability and low data requirements, AquaCrop is a practical tool to investigate the effect of weed infestation on crop production in data-scarce regions.

Box 4.1: Model comparison for simulation of weed-infested wheat fields

AquaCrop's performance to simulate wheat production for the experiment in Wagga Wagga (1998) was compared with the performance of ALMANAC, APSIM, CROPSIM and INTERCOM as reported by Deen et al. (2003). Simulated LAI values were converted to CC values using Equation 4.3 to enable model comparison. Models were compared based on the calculated RRMSE and RME (Box 2.1).

In spite of AquaCrop's limitations to accurately simulate wheat development during winter, Figure 4.6 shows that AquaCrop's performance to simulate crop canopy cover and biomass development was within the performance range of ALMANAC, APSIM, CROPSIM and INTERCOM. The five models covered a wide range from excellent to very poor performance, with RRMSE values of about 5 to 60%. AquaCrop simulations of crop canopy cover were most accurate of all models, apart from simulations for weed-free, water-stressed conditions for which AquaCrop performed second best. In contrast, AquaCrop's performance was amongst the poorest for simulation of biomass during the season. Particularly in water-stressed conditions, RRMSE values revealed very poor model performance. Nevertheless, APSIM, CROPSIM, and INTERCOM performed even worse for some water or weed treatments.

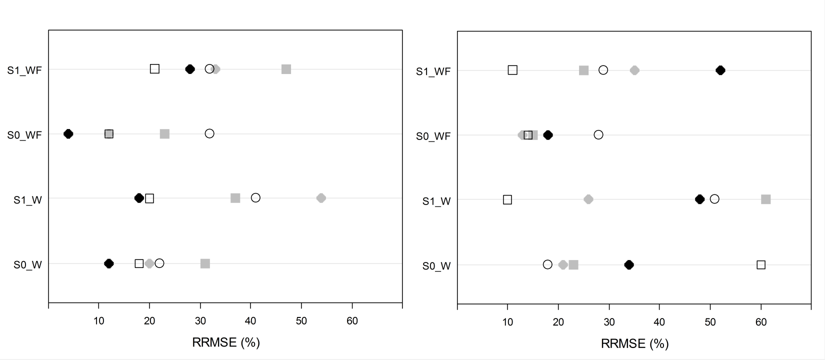


Figure 4.6: The relative root-mean-square error (RRMSE) for wheat canopy cover (left) and biomass during the growing season (right) varies between different models: AquaCrop (●), ALMANAC (●), APSIM(○), CROPSIM (■) and INTERCOM(□). Model performance also differs between water and weed treatments: absence (S0) or presence (S1) of water stress, weed-free (WF) or weed-infested (W).

Although biomass during the season was predicted rather poor, final biomass deviation (RME) was maximum 2% for AquaCrop (Figure 4.7).

With these small deviations, AquaCrop was superior to all other models that had RME values as big as 27% or -25%. While the other models systematically overestimated (ALMANAC and INTERCOM) or underestimated (CROPSIM and APSIM) final biomass, AquaCrop did not show systematic deviation. Final biomass at maturity was slightly overestimated in weed-infested conditions, but underestimated in weed-free plots.

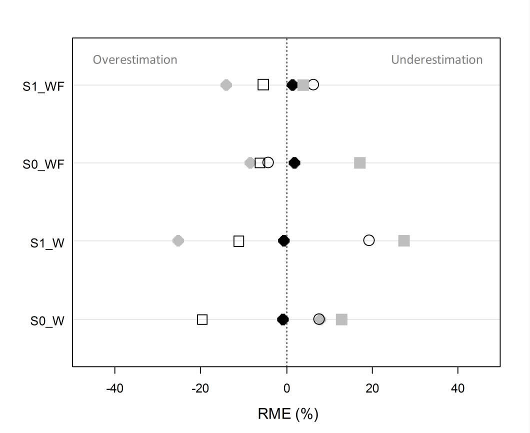


Figure 4.7: Relative model error (RME) for biomass at maturity varies between different models: AquaCrop (●), ALMANAC (●), APSIM(○), CROPSIM (■) and INTERCOM(□). Model performance also differs between water and weed treatments: absence (S0) or presence (S1) of water stress, weed-free (WF) or weed-infested (W).

Chapter 5

AquaCrop scenario analysis for development of environment-specific agricultural management strategies

This chapter is based on:
Van Gaelen, H, Raes, D, and Diels, J (2013). AquaCrop as a decision support tool to assess the effect of field management on crop water productivity. In: *Water, environment and agriculture: challenges for sustainable development - Proceedings of the 1st CIGR Inter-Regional Conference on Land and Water Challenges*. Ed. by Lamaddalena, N, Todorovic, M, and Pereira, LS. Bari, Italy, S4–6

&

Van Gaelen, H, Raes, D, and Diels, J (2014). A model based approach towards environment-specific field management strategies for upgrading crop water productivity. In: *Communications in Agricultural and Applied Biological Sciences - Proceedings of the 19th National Symposium on Applied Biological Sciences*. Vol. 79. Liege, Belgium, 15–20

5.1 Introduction

Due to the increasing world population and prosperity, global food production needs a 70% increase by 2050 according to the Food and Agriculture Organization (FAO, 2011). To achieve this in a sustainable way by taking into account the limited land and water resources, an increase in productivity needs to be accompanied by an increase in crop water productivity. Improved agricultural management is one of the key solutions for upgrading (crop) water productivity. Particularly, in drought-prone regions where crop production is determined by variable rainfall, dry spells and droughts, rather than by low total rainfall, improved agricultural management shows great potential to upgrade crop water productivity (Rockström et al., 2003; Wani et al., 2008).

Ample experimental research has been conducted to investigate the effect of agricultural management on crop (water) productivity. However, experimental research is time- and resource-consuming, certainly when several management options need to be evaluated. Moreover, the effect of agricultural management is strongly dependent on the complex interactions between rainfall pattern, soil characteristics and cropping system of a particular research site. Since experimental research results are affected by the specific experimental set-up, they can not be used to define general guidelines on efficient and sustainable agricultural management. By contrast, well calibrated crop models allow for efficient and extensive scenario analysis. Moreover, they contribute to the understanding of interactions between environmental and management factors, facilitate long-term assessments with historical climate data, and enable assessment of future climate scenarios. All this makes them suitable tools to assess crop response to agricultural management.

Several simulation studies have been conducted to assess the effect of agronomic practices and water-saving techniques on crop production for irrigated or rainfed cropping systems using crop models such as APSIM (e.g. Akponikpè et al., 2010; Kahinda et al., 2007), CropSyst (e.g. Jalota et al., 2010; Lehmann et al., 2013), AquaCrop (e.g. Abrha et al., 2012; Biazin and Stroosnijder, 2012; Shrestha et al., 2013b) and CERES (e.g. He et al., 2012; Rinaldi, 2004; Timsina et al., 2008). However, most of these studies evaluate agricultural management strategies for a specific case-study area, crop or cropping system whereby limited attention is paid to the interaction between management, crop and environmental factors. Also, most studies only consider a limited number of agricultural management options. Moreover, most simulation studies just assess the effect of different management scenarios on crop yield. Only few studies (Arora, 2006; Biazin and Stroosnijder, 2012; Jalota et al., 2010; Kahinda et al., 2007; Shrestha et al., 2013b; Timsina et al., 2008) tend towards more sustainable decision making by assessing the effect on both yield and crop water productivity.

This chapter presents a simulation approach to assess agricultural management strategies to optimize both crop yield and crop water productivity in rainfed cropping systems using the AquaCrop model (Hsiao et al., 2009; Steduto et al., 2009; Raes et al., 2009; Vanuytrecht et al., 2014a). With the goal to support development of environment-specific management guidelines, this simulation approach also intents to improve understanding of the interactions between management, soil, climate, and crop characteristics. An example scenario analysis for drought-prone rainfed cropping systems is conducted to assess the potential of the presented simulation approach and illustrate how simulation results can be analysed with special attention for management-environment interactions.

5.2 Simulation experiment

A simulation experiment was set up to assess the effect of several agricultural management practices on crop yield and crop water productivity for a wide range of rainfed cropping systems. By means of a factorial simulation experiment using the AquaCrop model, 10 agricultural management practices were studied for 81 different farming systems.

5.2.1 The AquaCrop model

A test version of AquaCrop 4.0 (AquaCrop 4.0*) was used for this simulation experiment. AquaCrop simulates crop productivity using a four-step process as discussed in Section 2.3. First, green crop canopy cover (CC) is simulated. In a second step, crop transpiration (Tr) is simulated considering reference evapotranspiration (ET_0) and a crop transpiration coefficient (Kc_{Tr}) that is proportional to the simulated canopy cover. Next, crop transpiration is converted into dry above-ground biomass production (B). In a final step, crop biomass is converted to crop yield (Y) by means of the harvest index (hi). Crop yield per unit of water evapotranspired (ET) is given by the ET crop water productivity (WP_{ET}). During this four-step simulation process, the model accounts for the effect of various abiotic stresses, including water stress, temperature stress, soil salinity stress and soil fertility stress (Section 2.5). In addition, the effect of several agricultural management practices can be taken into account as discussed in Section 2.6.

5.2.2 Cropping systems

By combining three different climatic conditions, crop varieties, soil types and soil fertility levels, 81 cropping systems were defined.

- **Climatic conditions**: Three different locations with varying climatic conditions were selected: Tunis (Tunisia), Mekelle (Ethiopia) and Chitedze (Malawi). Table 5.1 shows that these three locations cover the full range from semi-arid to sub-humid climatic conditions.
- **Crop variety**: Three barley (*Hordeum vulgare* L.) varieties, with a typical growing cycle length of 90 days (short), 105 days (medium) and 120 days (long)(FAO, 2007) were considered. Barley was selected as a crop because of its wide geographical distribution, its ability to grow in a wide variety of environments and its availability as calibrated crop in the AquaCrop database. All three varieties were simulated using the default

AquaCrop parameters calibrated by Abrha et al. (2012) (Table A.3). Only the time to senescence and maturity was adapted because varieties differed in the length of the mid-season stage. Crop parameters describing crop response to soil fertility stress were calibrated with the autocalibration procedure using the default settings: very strong CC_x reduction and medium canopy decline in the season for a relative biomass production (B_{rel}) of 50%.

- **Soil type**: Deep uniform soil profiles of three soil textural classes were considered: loamy sand, silt and clay loam. These textural classes were selected because they strongly differ in total available soil water (TAW), a major determinant of water availability to the crop. The default AquaCrop soil parameters for each soil textural class where used (Table A.1). Assuming that all soils are well structured, the default K_{sat} value for the silt soil was increased from the default of 50 mm/d to 100 mm/d in order to avoid excessive surface runoff.

- **Soil fertility level**: Three soil fertility levels, i.e. non limiting soil fertility (B_{rel} of 100%), moderate soil fertility (B_{rel} of 60%) and poor soil fertility (B_{rel} of 40%) were selected to represent differences in fertilizer use between various farming systems.

Table 5.1: Three selected locations with local average climatic conditions according to FAO (2005). The growing season is defined as the period in which rainfall exceeds 0.5 times the reference evapotranspiration (ET_0). The aridity index (AI) is the ratio of the annual rainfall and ET_0.

Location	**Chitedze**	**Mekelle**	**Tunis**
Country	Malawi	Ethiopia	Tunisia
Coordinates	13.98°S, 33.63°E	13.5°N, 39.48°E	36.83°N, 10.13°E
Altitude (m a.s.l.)	1149	2070	4
Climate			
Aridity	Sub-humid	Semi-arid	Semi-arid
Rainfall regime	monomodal	monomodal	monomodal
Annual rainfall (mm)	923	620	436
Annual ET_0 (mm)	1349	1497	1093
Annual AI (mm/mm)	0.68	0.41	0.4
Growing season			
Start	November	June	October
End	April	September	April
Average length (d)	153	88	172

5.2.3 Agricultural management

The effect of nine agricultural management practices was studied for each of the 81 cropping systems (Table 5.2). In addition, a reference simulation served as a standard to evaluate the effectiveness of the different management practices. This reference simulation only considered soil fertility management corresponding to the soil fertility level of the cropping system but no additional management practices.

Management practices like mulches, rainwater harvesting, and soil bunds are strategies that farmers implement to increase productivity beyond what is obtained under reference conditions. Other practices such as a restrictive soil layer and weed infestation are constraints under which farmers operate. Resolving these constraints might boost crop productivity. More detailed information on the required AquaCrop input, implementation and calculation procedures for the various agricultural management practices is presented in Chapter 2.

Table 5.2: Overview of different agricultural management practices that were evaluated for the 81 different cropping systems.

Management	**Symbol**	**Description**
Reference	Ref	Only soil fertility management
Mulches	M50	50 % evaporation reduction due to mulches
	M95	95 % evaporation reduction due to mulches
Field surface management	Bunds	Soil bunds of 0.25 m
	RWH	Rainwater harvesting, runoff agriculture with 10:1 catchment-to-cropping area ratio
Soil management	Restr	Restrictive soil layer at 0.5 m depth
	TAW+	TAW increased by 50 mm/m
	TAW-	TAW decreased by 50 mm/m
Weed management	W15	15% relative weed cover, crop more competitive than weed
	W30	30% relative weed cover, crop more competitive than weed

5.2.4 Simulation period, growing period and initial conditions

The simulation period was determined by availability of weather data for each location. A total of 30 growing seasons were simulated for cropping systems in Chitedze (1980-2010) and Mekelle (1961-1973, 1981-1985, 1988, 1992-2002), while only 23 seasons were simulated (1979-2001) for cropping systems in Tunis. Simulations started each year at the end of the dry period on 1 October for Chitedze, 1 June for Mekelle, and 1 August for Tunis. At that moment the initial soil water content was assumed to be at permanent wilting point due to the high ET_0 and limited rainfall in the dry period.

The first day of the growing period (sowing date) was generated by AquaCrop based on a rainfall onset criteria of at least 30 mm rainfall in a 5-day period for Chitedze and Mekelle and 25 mm in a 5-day period for Tunis. Searching for fulfilment of the onset criteria was started at 1 June in Mekelle, and 1 October in Chitedze and Tunis. Since farmers would not sow immediately after the first rains, the second occurrence of the criteria fulfilment was accepted as a sowing date for Mekelle and Tunis. For Chitedze the third occurrence was accepted because of the very irregular start of the rainy season (Scroyen, 2012). If no appropriate sowing day was found before 31 January (Chitedze), 31 August (Mekelle) and 31 December (Tunis), the season was considered as a season with harvest failure (yield equal to 0 t/ha) because of insufficient rainfall.

5.2.5 Impact analysis

The effectiveness of each agricultural management practice was assessed by means of the Y and WP_{ET} response given by:

$$P_{response,m} = \frac{P_m - P_{ref}}{P_{ref}} \cdot 100 \tag{5.1}$$

where $P_{response,m}$ is the average response (%) of productivity parameter Y (t/ha) or WP_{ET} (kg/m^3) to management practice m, P_m and P_{ref} is the average productivity (Y or WP_{ET}) under certain environmental conditions with and without management practice m respectively. Response values express the relative increase (positive response values) or decrease (negative response values) of the average Y and WP_{ET} for certain environmental conditions due to a certain management strategy in comparison to the reference management.

The Y and WP_{ET} response to all nine management practices was assessed for each cropping system. Furthermore, response values were analysed making a distinction between wet, dry and normal growing seasons for each location. Each of the 30 (Chitedze, Mekelle) or 23 (Tunis) simulated growing seasons was classified as dry, normal or wet based on a frequency analysis of seasonal rainfall

Table 5.3: Seasonal rainfall classes for every location with the number of seasons (n), average seasonal rainfall, standard deviation (SD) and coefficient of variation (CV) over the simulation period. Values with the same subscript do not differ at a 0.05 significance level.

Location	**Seasonal rainfall class**	n	**Seasonal rainfall** average (mm)	SD (mm)	CV (%)
Chitedze	Wet	8	1077.5_a	89	8.3
	Normal	15	830.0_b	58.1	7
	Dry	7	644.4_c	89.6	13.9
Mekelle	Wet	12	652.5_c	113.1	17.3
	Normal	4	470.8_d	44.3	9.4
	Dry	14	382.2_e	43.1	11.3
Tunis	Wet	8	507.2_d	84.7	16.7
	Normal	8	355.6_e	50.2	14.1
	Dry	7	216.3_f	44.9	20.8

with RAINBOW (Raes et al., 2006). Seasonal rainfall was calculated as the sum of the daily rainfall from November to April (Chitedze), June to September (Mekelle) and October to April (Tunis). Growing seasons with seasonal rainfall with an exceedance probability of at least 70% or less than 30%, were classified as dry and wet respectively, whereas all others were classified as normal growing seasons. Table 5.3, which shows the average seasonal rainfall for every seasonal rainfall class, indicates that the average seasonal rainfall in wet seasons in Mekelle was not significantly different from dry growing seasons in Chitedze. Similarly, normal and dry seasons in Mekelle did not differ significantly from the wet and normal growing seasons in Tunis respectively.

Since the effectiveness of management practices was analysed on the basis of average Y and WP_{ET} values, it also includes seasons in which grain yield was zero. By contrast, the frequency of failure years is very decisive for adoption of a management strategy by risk averse farmers. For that reason, additional analysis of the frequency of harvest failure, i.e. percentage of seasons with Y being 0 t/ha, was conducted.

5.3 Results

The average Y and WP_{ET} response to the nine different agricultural management strategies is depicted in Figure 5.1 and represents the increase or decrease of the average Y and WP_{ET} over all simulated growing seasons and cropping systems (combinations of crop type, soil type and soil fertility level) due to the implementation of these strategies. In Figure 5.1 responses are presented for different weather conditions (combinations of a location and seasonal rainfall) ranging from very dry (dry growing seasons in Tunis) to more humid (wet growing seasons in Chitedze). No responses are presented for dry growing seasons in Tunis as insufficient rainfall resulted in complete failure of harvest for all those seasons.

The four quadrants in each plot of Figure 5.1 distinguish the four potential effects of agricultural management, while the origin (0,0) of each plot corresponds to productivity obtained under the reference treatment. The lower left quadrant (III) displays the management practices that reduce both Y and WP_{ET}, while the upper right quadrant (I) shows the management strategies that increase both Y and WP_{ET}. The practices that increase Y while at the same reduce ET (e.g mulches) are located above the 1:1 line in quadrant Ia. Practices that merely increase WP_{ET} by increasing Y are located below that line (Ib). Furthermore, quadrant II contains practices that increase WP_{ET} despite a decrease in Y. When implementing these practices the importance of saving water has to be weighed against the yield decline. Finally, no points are located in quadrant IV, as it would contain strategies that increase Y while decreasing WP_{ET}. Practices for which the Y increase is offset by an even larger increase of ET are not realistic for rainfed farming.

Figure 5.1 shows that the effectiveness of the investigated management strategies was strongly determined by the weather conditions, with the exception of weed management. On the one hand, it can be observed that in the driest conditions (Tunis) none of the investigated practices were very effective to increase Y. In such dry conditions only (deficit) irrigation could upgrade productivity. On the other hand, in more humid conditions (e.g. wet seasons in Chitedze and Mekelle), practices that focus on saving water were less effective. In between (e.g. normal to dry seasons in Chitedze and Mekelle), mulches, rainwater harvesting and bunds were most effective, since they all increased water availability. Figure 5.1 also shows that mulching and weed control payed off under all weather conditions.

Furthermore, Figure 5.1 reveals unexpected effects of some of the agricultural management strategies. The effect of weed management appeared to be almost independent of weather, since W15 and W30 always caused a Y and WP_{ET} decline of about 10% and 21% respectively. In reality, one would expect that the competition for water between weeds and crop would lead to a much stronger Y decline in dry conditions than in more humid cropping systems. Furthermore, TAW− and TAW+ did not affect Y and WP_{ET} as one would expect by their ability to decrease or increase water availability. For many weather conditions TAW+ had a negative effect and sometimes it was even more detrimental for productivity than TAW−. Also, the effect of a restrictive soil layer was not always negative as one would expect. Rest increased Y and WP_{ET} amongst others in dry growing seasons in Chitedze.

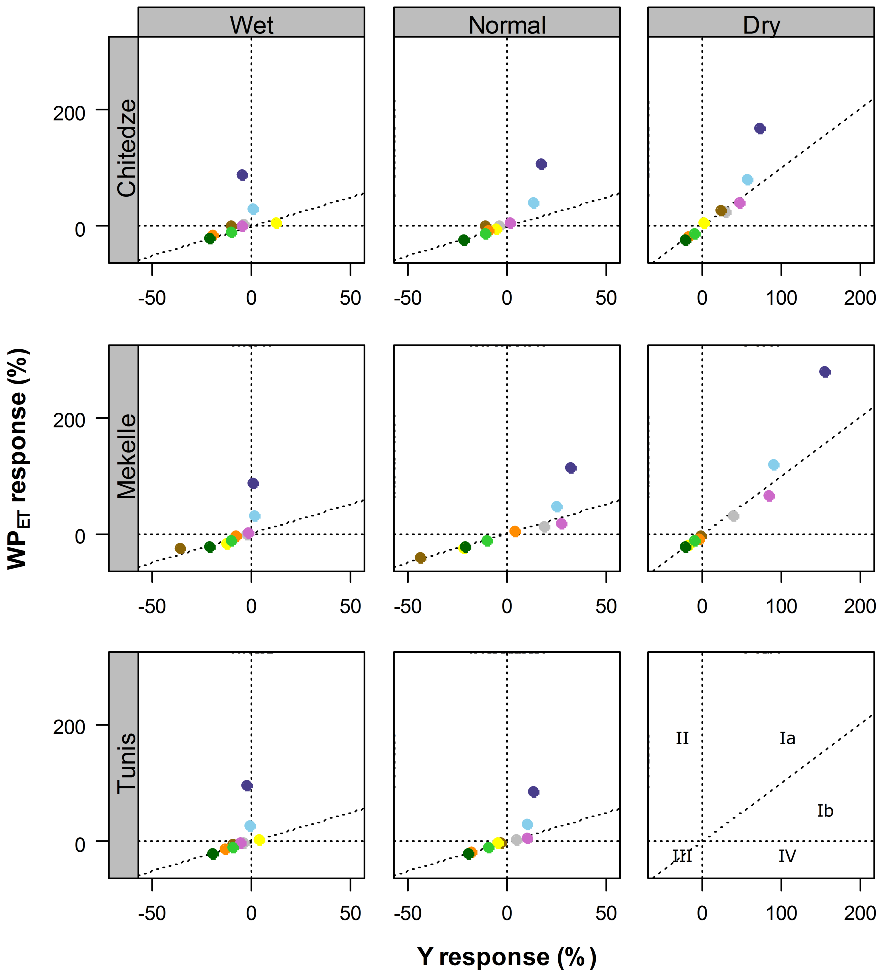


Figure 5.1: Average yield (Y) and crop water productivity (WP_{ET}) response to different agricultural management strategies, i.e. TAW− (●), TAW+ (●), Restr (●), Bunds (●), M50 (●), M95 (●), RWH (●), W15 (●), W30 (●) depends on the local weather conditions.

Despite the high dependency on weather conditions, Figure 5.1 also shows that for similar weather conditions, the most effective practices could differ. For example mulches were more effective for dry seasons in Chitedze compared to wet seasons in Mekelle, although both have similar seasonal rainfall (Table 5.3). This indicates that the effect of agricultural management is determined by more than just weather conditions, and that other agronomic and environmental factors should be taken into account when analysing simulation results.

Therefore, the average responses presented in Figure 5.1 were further explored by investigating all the individual responses for different cropping systems implied in those averages. An example is given by Figure 5.2 which zooms in on the normal growing seasons in Mekelle and displays all responses for different groups of cropping systems, i.e. different soil types (Figure 5.2a), soil fertility levels (Figure 5.2b) and crop varieties with different cycle lengths (Figure 5.2c).

Figure 5.2a clearly indicates that soil types influenced the effect of soil and field surface management. Although the average effect of Restr was negative in normal growing seasons in Mekelle (Figure 5.1), the response was much more negative for loamy sand soils compared to clay loam soils. For silt soils the response was sometimes even positive. Also the response to TAW+ and TAW− clearly followed a pattern related to soil types. For TAW+ the average response was positive (Figure 5.1) but that was mainly caused by a positive response on loamy sand soils. On clay loam soils and silt soils the response to TAW+ was even negative. For TAW−, on the other hand, the response varied from negative for a loamy sand soil to positive for a silt soil. Eventually this resulted in a negative average response (Figure 5.1). The fact that silt soils reacted contrary to expectations can be explained by the fact that aeration stress was observed for these simulations. Making the soil reservoir smaller by Restr or TAW−, relieved part of the aeration stress. Also, the effect of bunds and RWH was soil type dependent. The lower curve number value for loamy sand soils (Table A.1) resulted in lower surface runoff on these soils as compared to other soil types. Consequently, a smaller amount of water could be gained by RWH or bunds, which led to lower responses to those practices on loamy sand soils.

Next to soil type, Figure 5.2b shows that also the soil fertility level influenced the effectiveness of management strategies. For example, the Y response to mulch was smaller on poorly fertilized soils than on soils with non limiting soil fertility. Reducing evaporation with mulches might not be very effective on poorly fertilized soils because soil fertility limits crop production more than water availability. By contrast, the WP_{ET} response to mulches was stronger for poorly fertilized soils than for well fertilized soils. Since crop canopy development was less strong on poorly fertilized soils, also transpiration was lower and evaporation higher than on fields with non limiting soil fertility. For that reason, techniques that reduce evaporation such as mulches had a stronger WP_{ET} response for poorly fertilized soils.

Furthermore, the response to mulches was also dependent on the crop variety as shown in Figure 5.2c. Y response was smaller for crops with a short growing cycle than for crops with a long cycle. Crops with a short cycle experience less water stress because their crop cycle extends less far in the dry season. As such these short cycle varieties crops benefit less from additional soil water in the root zone due to mulches.

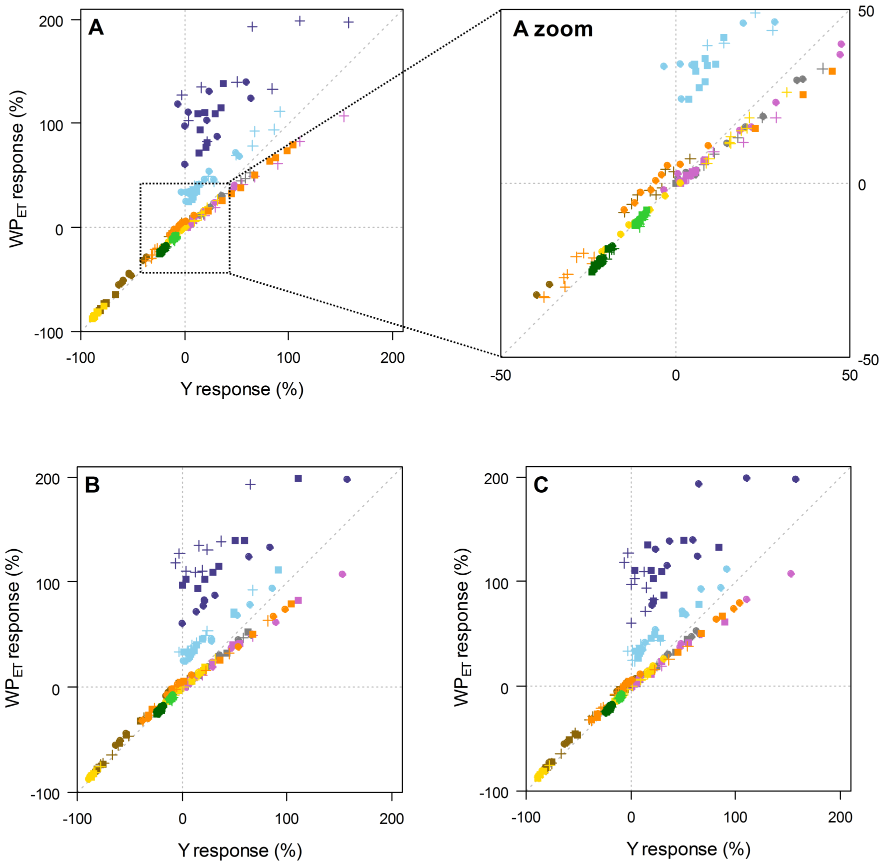


Figure 5.2: Average yield (Y) and crop water productivity (WP_{ET}) response to different agricultural management strategies, i.e. TAW− (●), TAW+ (●), Restr (●), Bunds (●), M50 (●), M95 (●), RWH (●), W15 (●), W30 (●) for normal growing seasons in Mekelle depends on (a) soil type, i.e. clay loam (●), loamy sand (■) and silt (+), (b) soil fertility level, i.e. non limiting (●), moderate (■) and poor (+), and (c) crop variety with long (●), medium (■) and short (+) cycle length.

Figure 5.1 and Figure 5.2 indicate which strategies could improve average Y and WP_{ET} under different environmental conditions. Additional analysis of the effect of agricultural management on the frequency of harvest failure (Figure 5.3) revealed, for example, that for dry seasons in Mekelle the water saving practices that were most beneficial for Y and WP_{ET} (bunds, RWH, M50, M95, Figure 5.1) also decreased the occurrence of harvest failure. Inadequate weed management, on the other hand, decreased Y and WP_{ET} substantially, but did not affect the occurrence of crop failure. In addition, it is clear from Figure 5.3 that the effect of management on the frequency of harvest failure is highly dependent on the soil type of the cropping system.

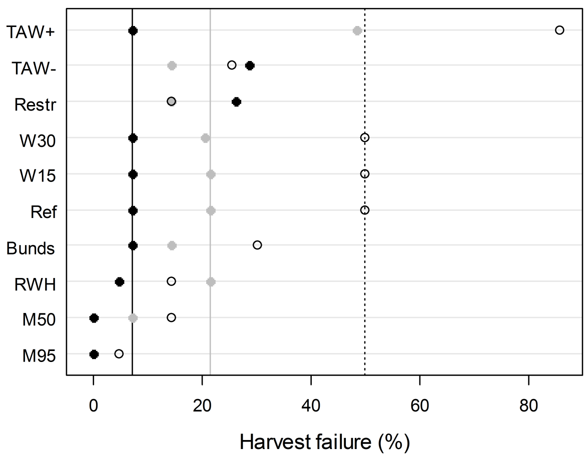


Figure 5.3: The average percentage of the dry growing seasons in Mekelle with complete harvest failure ($Y = 0\,\mathrm{t/ha}$) on clay loam (●), loamy sand (●) and silt (○) soils for different agricultural management strategies. The failure percentage for reference management on each soil type is marked with a vertical line.

5.4 Discussion

The presented scenario analysis served to illustrate the AquaCrop-based simulation approach to investigate the effectiveness of different agricultural management practices. Hence, it was by no means intended to present the optimal management strategies for the simulated regions, nor to present exact responses that can be expected in farmers' fields. The presented response values are merely indicative and serve as a starting point to compare the effect of various management practices and to explore management-environment interactions.

The proposed simulation approach supports development of agricultural management guidelines that promote a sustainable increase of agricultural productivity. This is due to the fact that the AquaCrop-based approach allows assessment of both Y and WP_{ET} response to agricultural management. Since water is or is becoming a bottleneck for increasing agricultural production in many regions of the world, the WP_{ET} response to agricultural management is as important as the Y response. In very dry regions one can even consider implementing management practices that increase WP_{ET} while the effect on Y is insignificant or slightly negative. In addition, the simulation approach promotes sustainable management practices because management-environment interactions are explicitly accounted for. The presented scenario analysis for drought-prone rainfed farming systems confirmed that the effect of management strongly depends on the environmental conditions. Due to the strong interaction between management, crop, soil and climate, it is crucial that agricultural management strategies are tailored to the local weather conditions, environment and farming system to get the highest Y and WP_{ET} benefits. Furthermore, consideration of the management-environment interactions, makes that the effect of environmental changes on the effectiveness of agricultural management can be considered in the analysis. For example, the effect of climate change on the effectiveness of agricultural management practices could be investigated, although not illustrated for the presented scenario analysis. This could indicate whether agricultural management practices that are effective under current environmental conditions will remain effective in the future as well. A good example was set by Lehmann et al. (2013) who studied the impact of different climate change scenarios on optimal fertility and irrigation management using CropSyst in combination with an economic decision model.

Furthermore, even though management decisions are to be customized for each cropping system, the AquaCrop simulation approach is applicable for scenario analysis and development of management guidelines on a large spatial scale. For that purpose AquaCrop can be implemented in a GIS environment following the example of Lorite et al. (2013) with AquaGIS or Thorp and Bronson (2013) with the GeoSim toolbox. In that manner, spatial differences in environmental conditions can be linked to spatial differences in productivity and effectiveness of management practices. Furthermore, strategic decisions regarding agricultural management require analysis of their effect in multiple growing seasons. Therefore, simulations should be conducted for a long time series of (historical) weather data. As demonstrated by this study, such a scenario analysis over many growing seasons allows to study the interaction between management and weather conditions, as well as the effect of agricultural management on inter-annual Y and WP_{ET} variability. Running AquaCrop simulations for large spatial or time scales is facilitated by the use of the graphical user-interface and project modus of AquaCrop, as well as the small computation times of the model. The latter can be further optimized by using the AquaCrop plug-in software. In addition, Lorite et al. (2013) developed the AquaData tool to facilitate input and output data processing for extensive AquaCrop simulation studies.

The presented simulation approach has some limitations which affect results and consequently need consideration when using the approach to develop management guidelines. First, it is important to note that the presented scenario analysis was purely based on model simulations without any field validation. Ideally, field observations of soil characteristics, crop characteristics, crop development and production should be collected to complement the simulations. On the one hand, such field observations can serve to calibrate the AquaCrop model parameters to match the local farming conditions in order to improve the accuracy of simulation results. On the other hand, field observations can be used to validate simulation results. In addition, field experiments can also complement the simulation approach by testing management practices with high potential under realistic agronomic conditions in farmers' fields.

Moreover, the presented AquaCrop-based approach is affected by limitations of the AquaCrop model itself. Scenario analysis is confined to the management practices implemented in AquaCrop. Though extensive options are available as discussed in Section 2.6, some management practices such as disease control and intercropping can not be simulated using AquaCrop. Furthermore, some of the calculation procedures for agricultural management, implemented in AquaCrop 4.0*, need to be improved. The presented scenario analysis showed that the simulated effect of practices affecting the soil water holding capacity (TAW−, TAW+ and Rest) was sometimes counter-intuitive. These unexpected results are most likely caused by the fact that AquaCrop evaluates water stress by evaluating the soil water content over the complete root zone, without taking into account neither water nor root distribution within the soil profile. For example, AquaCrop might simulate the presence of water stress when only the topsoil is wet and the rest of the root zone is dry. In reality, a crop might not suffer from water stress since the majority of roots is located in the topsoil where sufficient water is available. Hence, a future update of the AquaCrop water stress calculation procedures seems necessary to improve simulation of crop responses to water stress and the way that these responses are influenced by agricultural management. Next, the simulated Y and WP_{ET} decline due to the presence of a restrictive soil layer is most likely overestimated. In the AquaCrop simulation procedure, a restrictive layer completely stops root development, while in reality such a layer would only slow down root expansion. Since some roots can reach deeper soil layers and extract water despite the presence of a restrictive layer, the crop is less vulnerable to water stress than what is simulated by AquaCrop. Moreover, the presented scenario analysis showed that the effect of weed management was almost independent of the environmental conditions of the cropping system. Clearly, the weed management procedure as implemented in AquaCrop 4.0* did not accurately capture the weed-environment interactions and needs to be revised. Such a new weed management procedure has been developed in the framework of this PhD research and is presented in Chapter 4.

Furthermore, evalation and comparison of various management strategies in the presented scenario analysis completely relied on assessment of average Y and WP_{ET} response values. However, one should take care when disregarding the absolute Y and WP_{ET} numbers. Also, Rockström and Barron (2007) mention that Y and WP_{ET} responses to agricultural management are potentially higher when the absolute reference Y is low. Increasing Y from a level that is already substantially high, on the other hand, does not necessarily lead to large WP_{ET} responses. Moreover, next to the average Y and WP_{ET} levels, it is crucial to assess inter-annual productivity variability. In this study yield variability was only briefly touched upon by evaluation of the harvest failure frequency. More detailed analysis of the complete distribution of Y and WP_{ET} under various management strategies and environmental conditions could be done by means of cumulative probability density functions, or summarizing statistics such as the coefficient of variation.

Although the proposed modelling approach might provide valuable insights to optimize agricultural management, it can not stand by itself. Research results need to be placed in a broader context and further evaluated with respect to the institutional and socio-economic factors that determine successful adoption and implementation of the proposed management practices. For example, while this study demonstrated the strong interaction between seasonal rainfall and effectiveness of the various management strategies, farmers are unable to control weather conditions nor to adapt management to the expected rainfall every season. Risk-averse behaviour makes that smallholder farmers mostly prefer practices that optimize productivity and limit harvest failure in the dry seasons if crop production is already satisfactory in normal and wet years (Kijne et al., 2009). Hence, the high potential strategies that are indentified with the simulation approach, should be further evaluated from an institutional and socio-economic point of view. To evaluate the economic feasibility of certain practices, the presented simulation approach could be extended by linking AquaCrop to an economic model. Examples have been presented by García-Vila et al. (2009), García-Vila and Fereres (2012) and Cusicanqui et al. (2013) who used a combination of AquaCrop and an economic model to optimize irrigation management. Furthermore, the large scale effects of agricultural management need to be evaluated before being implemented. While certain practices might increase water availability at field scale, they might be detrimental for water availability in the region. To investigate both the field and catchment scale effects of agricultural management, AquaCrop could be linked to hydrological models as demonstrated in the following chapters (Chapter 6 and 7).

5.5 Conclusion

This study presented and illustrated an AquaCrop-based simulation approach to evaluate a broad range of agricultural management strategies for upgrading crop (water) productivity in drought-prone rainfed cropping systems. By accounting for the complex interactions between management, soil properties, crop characteristics, and current or future climatic conditions, the simulation approach enables development of management strategies that are tailored to the local agronomic and environmental conditions. Furthermore, using the approach one could study the effect of various agricultural management practices on grain yield and crop water productivity at the same time. This makes the approach useful for regions where water availability is limited or is likely to become a bottleneck for increasing agricultural productivity. Finally, the wide-ranging applicability, the graphical user-interface and limited computation times, together with the ability to combine the model with additional tools make AquaCrop a practical tool for extensive agricultural management scenario analysis.

Chapter 6

Development and evaluation of the AquaCrop-Hydro model

This chapter is based on:
Van Gaelen, H, Willems, P, Diels, J, and Raes, D (2016b). Bridging rigorous assessment of water availability from field to catchment scale with a parsimonious agro-hydrological model. *Environmental Modelling & Software*, (Under Review)

6.1 Introduction

Crop simulation models integrate various processes in the soil-crop-atmosphere continuum that determine crop growth and production. Hence, they are useful tools to investigate management strategies to optimize crop productivity and resource use efficiency. Such investigations usually focus on one individual field because of the point-based nature of most crop models. However, optimization of the use of resources, particularly water, is not a local issue. A management strategy that optimizes crop water productivity in one farmer's field, may only be successful if it does not negatively affect neighbouring farmers. On an even larger scale, agricultural water management affects a whole catchment where different stakeholders, including households, industry and ecosystems, with different goals are making use of the available water resources (Bergez et al., 2012). It is clear that management strategies that are optimized for crop water productivity by a crop model, may fail to result in sustainable water use because catchment processes are disregarded.

Hydrological models, by contrast, simulate hydrological processes in a catchment and simulate crop transpiration as a part of the catchment soil water balance. However, as these models primarily focus on the simulation of hydrological processes, they rarely consider crop growth and management practices affecting crop transpiration and production explicitly. The hydrological models that do include physically based equations to estimate crop transpiration, such as the (semi)-distributed SWAT (Arnold et al., 1998; Douglas-Mankin et al., 2010), MIKE SHE (Refsgaard and Storm, 1995) and APEX (Gassman et al., 2010) models, show relatively high computational complexity. Moreover, they require a vast amount of data and elaborate calibration, or make use of parameters that are difficult to measure in the field. Despite the trend to apply remote sensing data as input or calibration data for agro-hydrological models (Boegh et al., 2004; Moulin et al., 1998), data availability remains a widespread issue (Grayson et al., 2002). Consequently, the application of such data-demanding models renders time- and resource-consuming, or even infeasible in data-scarce regions.

These limitations of existing crop and hydrological models urge for another approach. A coupling between both types of models, combining their advantages and functionality, can be a solution to obtain simple and widely applicable agro-hydrological models that (i) simulate crop production and water productivity at field scale, as well as up-scale their effects on hydrological processes and water availability at catchment scale, (ii) consider the effect of management and environmental changes on crop transpiration, crop productivity and catchment hydrological processes, (iii) require a feasible amount of easily obtainable input data and parameters to be calibrated, without compromising much the accuracy of the model results.

Previous attempts have been made to couple crop and hydrological models to capitalize the strengths of both and enable accurate investigation of agricultural management and environmental changes within a catchment. The WOFOST crop model (Boogaard et al., 2014) has been coupled to MetaSWAP (van Walsum and Supit, 2012) and to the distributed WEP-L model (Jia, 2011) for climate change impact assessment. Also, the DAISY crop model (Abrahamsen and Hansen, 2000) has been combined with MIKE SHE for investigation of nitrogen fluxes in agricultural catchments (Styczen and Storm, 1993; Thorsen et al., 2001). DSSAT crop models (Jones et al., 2003) have been linked to hydrological models to optimize irrigation management and drainage design (McNider et al., 2014; Singh and Helmers, 2008). Also extensive modelling systems, which integrate all aspects, dimensions, scales and actors involved in agricultural management, link crop and hydrological models (Jakeman and Letcher, 2003; Letcher et al., 2006).

However, most of these model combinations fail to fit all three above mentioned criteria. Being based on the distributed physically based model MIKE SHE, high data requirements remain an issue for the DAISY-MIKE SHE model (Boegh et al., 2004; Thorsen et al., 2001). The same is true for agro-hydrological models based on the data-demanding DSSAT crop models (Jones et al., 2003) and the fully integrative modelling systems (Jakeman and Letcher, 2003). Moreover, when developed for a specific application, the existing model combinations are only applicable for a certain region or crop (McNider et al., 2014). Also, problems to accurately represent spatial heterogeneity within the catchment due to the fixed model structure or grid size of the submodels should be mentioned

(Bithell and Brasington, 2009; Thorsen et al., 2001).

Therefore, the aim of this study was to develop a parsimonious, physically sound and widely applicable agro-hydrological model, AquaCrop-Hydro, to simulate crop productivity and water availability in agricultural catchments without vast data requirements for model input and calibration. The new model was developed by extending the AquaCrop crop water productivity model (Hsiao et al., 2009; Steduto et al., 2009; Raes et al., 2009; Vanuytrecht et al., 2014a) with a lumped conceptual hydrological model to simulate catchment hydrology. The performance of AquaCrop-Hydro to simulate crop production as well as discharge at the catchment outlet was evaluated for an agricultural catchment in Belgium.

6.2 Methodology

6.2.1 The AquaCrop-Hydro model

Figure 6.1 depicts the AquaCrop-Hydro model flowchart. AquaCrop-Hydro applies a semi-distributed approach, as it requires the catchment area to be divided into homogeneous land units (LUs) with similar land use, soil and agro-climatological characteristics. A model user can describe an LU as small as an individual field if detailed field observations are available, but it can be larger when its characteristics originate from basic information from literature, maps, agricultural statistics or farmer knowledge. For each LU, crop production and the soil water balance are simulated using AquaCrop (version 5.0), a simple process-based crop water productivity model. Next, the soil water balance at catchment scale is derived from simulated soil water balance components of all individual LUs. Subsequently, river discharge at the catchment outlet is simulated by means of a lumped conceptual hydrological model, derived from the generalized conceptual model structure (VHM conceptual model) by Willems (2014). Model simulations are conducted on a daily time step. The different simulation steps are further elaborated in the following paragraphs.

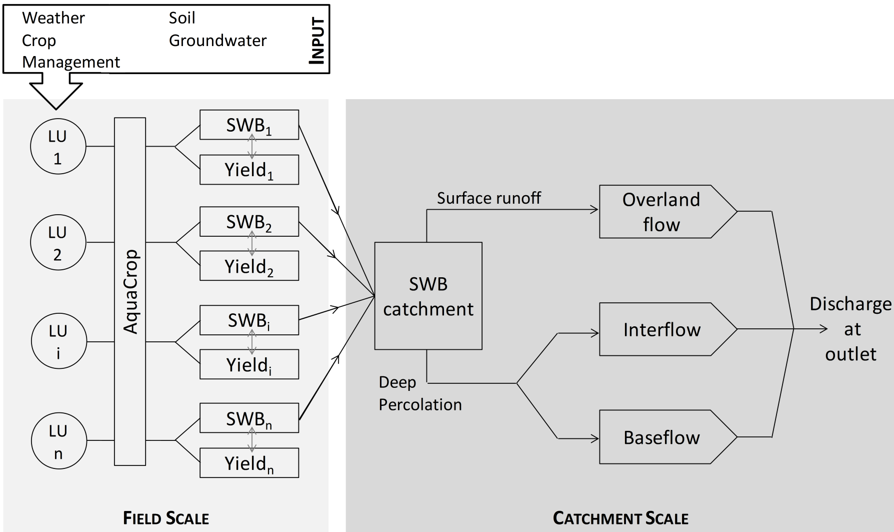


Figure 6.1: Flowchart of the AquaCrop-Hydro model presenting how AquaCrop simulates crop productivity and the soil water balance (SWB) for each land unit (LU). SWB simulations for each LU are scaled up to a catchment soil water balance and translated into different subflows, which sum up to the total discharge at the catchment outlet.

AquaCrop simulation of soil water balance and crop production at field scale

AquaCrop simulates daily crop canopy cover development, transpiration, dry above-ground biomass production, yield and the soil water balance, based on user-specified inputs of weather, crop characteristics, soil and groundwater properties as well as management practices of the cultivated field (Figure 6.1). While the field scale soil water balance is calculated for each day of the simulation period, crop development and production simulations are confined to the crop growing period. A simulation period can span several years and include several crop growing or fallow periods.

Since AquaCrop is a water-driven model, crop biomass and yield production are simulated proportional to the amount of water transpired by the crop. Transpiration, in its turn, depends on the simulated crop canopy cover and weather conditions. The simulated amount of crop yield per unit evapotranspiration is defined as the crop water productivity (Section 2.3). During this simulation process, the model accounts for the effect of agricultural management (Section 2.6) as well as various abiotic factors, including water stress, temperature stress, soil salinity stress and atmospheric CO_2 concentration (Section 2.5).

Crop growth and production are adjusted to water stress on the basis of the simulated soil water content in the root zone. Therefore, AquaCrop calculates the daily soil water balance considering incoming (rainfall, irrigation, capillary rise) and outgoing (surface runoff, deep percolation, evaporation, crop transpiration) water fluxes. More information on the calculation of the soil water balance with all its components is presented in Section 2.4.

Since AquaCrop was developed specifically for herbaceous crops, simulation of LUs with other land use requires specific settings. A bare soil can be simulated by setting the sowing date of the crop after the period of interest. An impervious surface can be simulated by bare soil settings in combination with a high surface runoff curve number (CN) value. An open water surface can be simulated as a bare soil with very low permeability and the presence of soil bunds that ensure water storage in the reservoir. Finally, grassland and forest can be simulated by specifying crop parameters that describe the typical canopy cover development of grass and trees, respectively. Examples for these land uses have been published for alfalfa (Kim and Kaluarachchi, 2015), olive trees (Rallo et al., 2012), tea plantations (Elbehri et al., 2015), poplar (Horemans et al., 2016) and jatropha (Segerstedt and Bobert, 2013).

From field to catchment scale

Scaling up the field scale AquaCrop results to catchment scale was done as suggested by Wesseling and Feddes (2006). After running AquaCrop for all individual LUs, the different components of the catchment soil water balance (rainfall, irrigation, evaporation, transpiration, surface runoff, capillary rise and deep percolation) and resulting soil water content are simulated as the weighted average of simulation results from all LUs:

$$X = \sum_{i=1}^{n} a_i \cdot x_i \tag{6.1}$$

where X is the soil water balance component or soil water content for the whole catchment, x_i is the soil water balance component or soil water content as simulated for landunit i, a_i is the fraction of the catchment area that is covered by landunit i, and n the number of landunits in the catchment. By adopting this semi-distributed approach, the spatial distribution LUs within the catchment is disregarded.

Simulation of catchment hydrology

The simulated catchment soil water balance is used to simulate discharge at the catchment outlet by means of a lumped conceptual hydrological model, derived from the generalized (VHM) conceptual model structure by Willems (2014). Similar to the VHM model structure, AquaCrop-Hydro simulates total discharge at the catchment outlet as the sum of three subflows: baseflow, interflow and overland flow (Figure 6.1). Overland flow corresponds to water that is generated by saturation or infiltration excess and reaches the river relatively fast via transport over land. By contrast, interflow and baseflow is water that has infiltrated into the soil and reaches the river outlet through subsurface transport. While interflow represents the quicker lateral flow in the unsaturated zone, baseflow corresponds to the slower flow via the groundwater or saturated zone.

The conceptual model represents each subflow by a reservoir with daily water in- and outflow as well as storage. Time variability of each subflow is simulated according to a linear reservoir equation:

$$Q_{out}(t) = exp\left(\frac{-1}{k}\right) \cdot Q_{out}(t-1) + \left(1 - exp\left(\frac{-1}{k}\right)\right) \cdot \frac{Q_{in}(t-1) + Q_{in}(t)}{2} \quad (6.2)$$

where $Q_{out}(t)$ and $Q_{in}(t)$ are the in- and outflow of the linear reservoir at time step t, and k is the reservoir recession constant. The recession constant corresponds to the time in which Q_{out} is reduced during dry weather ($Q_{in} = 0$) to 37% of the flow value at the start of the dry weather period.

The rainfall fraction contributing to each subflow (Q_{in}) is determined by the simulated catchment soil water balance. Surface runoff contributes to the overland flow reservoir. Deep percolation contributes to both the interflow and baseflow reservoir. Depending on the catchment's behaviour, the fraction of deep percolation going to the baseflow ($\mathrm{p_{BF}}$) or interflow (1- $\mathrm{p_{BF}}$) reservoir can either be considered constant or be defined as a function of the simulated soil water content.

6.2.2 Testing AquaCrop-Hydro

Study area

The Plankbeek stream is located in the sandy loam region of Flanders, Belgium (Figure 6.2). This area is characterised by a temperate climate with mild winters and cool summers, with rainfall uniformly spread over the year. The catchment upstream of the Huise/Plankbeek station (50°54'N, 3°34'E, 17 m a.s.l) covers an area of 4.5 km^2 and ranges in altitude between 70 m a.s.l. upstream and 17 m a.s.l. at the catchment outlet (AGIV, 2006). Silt loam soils dominate the catchment (about 96%), but sandy loam (about 4%) soils are found in the upstream area. Soils in the lowest area of the catchment, mainly around the river, are poorly drained (DOV, 2014). Agriculture is the dominant land use covering about 94% of the catchment. The remaining land consists of open water surfaces (0.7%), deciduous forest (0.2%) and impervious surface (5%). While about 18% of the agricultural land is used as grassland, crops, including winter wheat (20%), potato (16%), maize (14%) and sugar beet (11%), occupy the majority of the land. Outside the main growing season the majority of fields is left bare, although also grassland (7%) and cover crops (15 %) are found (AGIV, 2014, 2001; VLM, 2014).

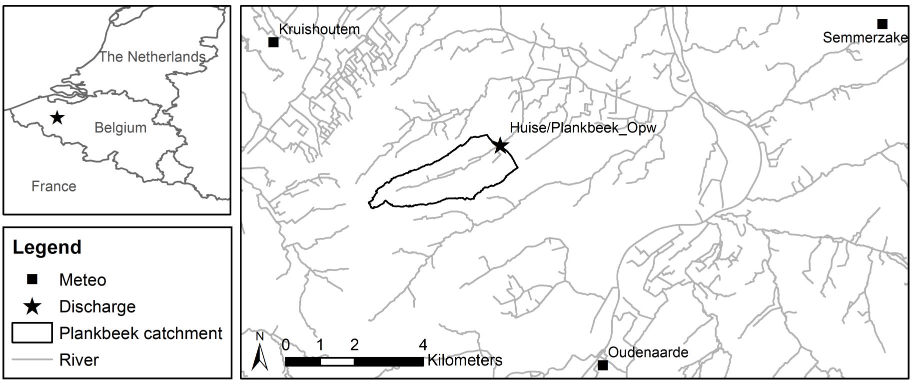


Figure 6.2: Location of the Plankbeek catchment with indication of the discharge measurement station at the catchment outlet and nearby meteorological stations.

Model input

AquaCrop-Hydro was ran for a 15-year period from 1/1/2000 to 31/12/2014 using a daily time step. Daily weather data were obtained from nearby meteorological stations (Figure 6.2) of the Royal Meteorological Institute (KMI). Average catchment rainfall was based on rainfall records of the station of Kruishoutem (50°56’N, 3°31’E, 9 m a.s.l.) and Oudenaarde (50°51’N, 3°37’E, 14 m a.s.l.) using the Thiessen polygon method. Daily minimum and maximum temperature (T_{min} and T_{max}) recorded at the station of Semmerzake (50°56’N, 3°40’E, 37 m a.s.l.) were used. Reference evapotranspiration was calculated with the FAO Penman-Monteith method using daily data from the station of Semmerzake (T_{min} and T_{max}, minimum and maximum relative humidity, average wind speed) supplemented with measurements of sunshine hours at the station of Melle (50°59’N, 3°49’E, 15 m a.s.l).

In addition to weather data, AquaCrop-Hydro required input of crop, soil, groundwater and field management characteristics for every simulated LU (Figure 6.1). For this research, 47 LUs were defined as a unique combination of soil texture, land use and crop rotation (AGIV, 2014, 2001; DOV, 2014; VLM, 2014). Crop rotations, being a combination of a main and after season crop (e.g. maize followed by grass), were derived from parcel data for the period 2000-2014 (VLM, 2014). Crop rotations that occupied on average less than 0.5% of the agricultural area were joined into a single LU for which no simulation was ran. Instead, the weighted average results of other agricultural LUs with the same soil type were assigned to this LU. Since land use and the type of cultivated crops was rather stable in the catchment over time, the type and number of LUs were kept constant over the 15-year simulation period. Each LU was assigned a constant relative area value (a_i in Equation 6.1) corresponding to its average relative area over the simulation period (2000-2014). An overview of all LUs and their relative area is presented in Table B.1.

Crop parameters (Table 6.1) for the most prevalent crops, i.e. winter wheat, potato, maize and sugar beet, have already been calibrated for Belgium by Vanuytrecht (2013) and Vanuytrecht et al. (2016, 2014c) and could directly be used for this study. The same is true for green bean crop parameters. For other crops, published crop parameters or information from literature (Abrha et al., 2012; Allen et al., 1998; Paredes et al., 2013; Vanuytrecht, 2013) were used to select crop parameters that match the local cultivation practices and crop varieties. Most attention was paid to canopy and root related parameters, which affect transpiration and the soil water balance most, and to which the model is very sensitive (Vanuytrecht et al., 2014b). Moreover, crops with similar characteristics and growing cycle were assigned the same set of crop parameters. For example, sugar beet parameters were used for simulation of fodder beet, while grass parameters were used for simulation of grass-clover mixtures, clover and other cover crops. This simplification reduced the number of AquaCrop simulations to 31, compared to 47 LUs (Table B.1). Representative sowing dates were selected according to local farming practices. To allow temperature dependent crop canopy development, all simulations were ran in growing degree mode, with the exception of forest and grassland for which a fixed growing cycle length can be assumed. The complete set of crop parameters for each crop is presented in Table B.3.

Table 6.1: Overview of simulated crops and key crop parameters. The percentage of the catchment area covered by the crop during the main growing season was derived from parcel data for the period 2000-2014 (VLM, 2014). Presented crop parameters include growing cycle length (mat) expressed in growing degree days (GDD) or calendar days (d), maximum canopy cover (CC_x) and corresponding maximum crop coefficient (kcx), as well as maximum effective rooting depth (rtx) and reference harvest index (hio). Crops indicated with + were simulated using the same set of parameters. The complete set of crop parameters is presented in Table B.3.

Crop	**Area (%)**	**Planting or regrowth***	**mat (GDD or d)**	CC_x **(-)**	**kcx (-)**	**rtx (m)**	**hio (%)**	**Main reference for crop parameters**
Winter wheat	19	25 Oct	1900 GDD	0.92	1.1	1.5	52	Vanuytrecht (2013)
Winter barley	1	1 Oct	1900 GDD	0.92	1.1	1.3	33	Abrha et al. (2012) and Vanuytrecht (2013)
Maize	14	25 Apr	1200 GDD	0.87	1.05	1.1	52	Vanuytrecht et al. (2016, 2014c)
Sugar beet	11	15 Apr	1850 GDD	0.98	1.1	1	70	Vanuytrecht et al. (2016)
+ Fodderbeet								
Potato	15	25 Apr	1850 GDD	1	1.1	0.6	90	Vanuytrecht et al. (2016)
Green beans	1	1 Jun	870 GDD	1	1.1	0.6	22	Vanuytrecht (2013)
Peas	6	1 Apr	945 GDD	0.9	1.1	0.5	34	Paredes et al. (2013)
Carrot	4	15 May	1850 GDD	0.95	0.95	0.6	60	Allen et al. (1998) and Vanuytrecht (2013)
+ Chicory								
Grassland	18	15 Mar	215-365 d**	0.9	0.85	0.6	85	Allen et al. (1998)
+ Clover								
+ Grass-clover								
+ Cover crop								
Deciduous Forest	0.2	15 Mar	231 d	0.9	0.95	1.5	-	Allen et al. (1998)

* Sowing or planting for annual crops, regrowth for perennials

** Growing cycle length varies depending on the temporary or permanent character of the grassland

Default soil parameters (saturated hydraulic conductivity, soil water content at saturation, permanent wilting point and field capacity) were selected from the AquaCrop database (Table A.1) for both the silt loam and sandy loam textural class. Curve number values (Table B.2) were selected on the basis of soil type, land use and crop type according to USDA (2007). Due to lack of information on the groundwater depth in the catchment, capillary rise from the groundwater table was neglected.

Furthermore, according to general practices in Flanders, most farmers do not irrigate and apply sufficient fertilizers to assure non limiting soil fertility for crop production. LUs with a bare soil, water surface or impervious area were simulated as described above in Subsection 6.2.1. Thereby, the saturated hydraulic conductivity of the bottom of the water reservoirs was set to 1 mm/d and the bund height to 10 m to ensure that reservoirs would not dry out. AquaCrop simulations started at 1/1/2000 with the initial soil water content at field capacity for all LUs.

The catchment soil water balance and soil water content were calculated using Equation 6.1, with a_i being the average relative area of each LU over the simulation period (2000-2014). Due to the variation of rooting depth during the growing season and between different crops, the catchment soil water content was calculated from the soil water content in the top 2 m of soil of each LU.

The lumped conceptual hydrological model did not require additional input data, but required calibration of the hydrological model parameters.

Model evaluation

AquaCrop-Hydro simulations of discharge were evaluated using daily average discharge observations from the station Huise/Plankbeek_Opw (VMM, 2015) located at the catchment outlet (Figure 6.2). Since no discharge observations were available for 1/1/2000-8/6/2002, this was considered as the warming-up period for the model. The remaining period of 12.5 years between 9/6/2002 and 31/12/2014 was considered for model evaluation. Hydrological model parameters were calibrated for the period 9/6/2002 to 15/8/2010 (about 8 years), while model simulations were validated for 15/8/2010 to 31/12/2014 (about 4.5 years). The 400 days (110 in calibration and 290 in validation period) for which discharge data were missing were excluded when comparing model results with the observations.

The hydrological model was calibrated according to the stepwise procedure ('VHM approach') by Willems (2014). This procedure implies that model structure identification and calibration is done simultaneously based on information about the catchment runoff response to the meteorological inputs.

This information on catchment response behaviour is derived after river flow time series processing using WETSPRO (Willems, 2009). Thereby the observed discharge is separated into different subflows (baseflow, interflow and overland flow) by means of a generalized Chapman-filter. The subflow separation process is based on three parameters that are determined by visual inspection of the flow time series. First, the recession constant (k) of the subflow is identified by analysing the slopes in different parts of the recession limbs of the hydrographs during long dry periods. The second filter parameter (w) is selected by optimizing the height of the subflow during a recession period. The w parameter can either be chosen to be constant or variable depending on the total discharge. Finally, a backward time shift is applied to compensate for the delayed subflow filter result in comparison with the total flow. More details on the subflow filtering, illustrated by an example, is given by Willems (2009).

The WETSPRO filter parameters, defined by visual inspection of the time series, to separate daily average discharge at the outlet of the Plankbeek catchment into subflows is presented in Table 6.2. The WETSPRO values for the subflows' recession constants were directly used as recession constants in AquaCrop-Hydro's linear reservoir equations (Equation 6.2).

Table 6.2: WETSPRO parameters for filtering average daily discharge measurements at Huise/Plankbeek_Opw station for period 9/6/2002-31/12/2014. Discharge was separated into baseflow, interflow and remaining overland flow.

Filter parameter		**Baseflow**	**Interflow**	**Overland flow**
Recession constant k	(d)	35	2	0.3
Time shift	(d)	3	0	
Filter parameter w	(-)	exponential	constant	
		0.2 to 0.65	0.6	

Also the equation to split deep percolation into a baseflow and interflow fraction (Equation 6.3) was identified and calibrated based on the filtered subflows. The selected equation simulates that baseflow decreases linearly when the total soil water content in the top 2 m of soil (SWC) varies between field capacity and the maximum soil water content of the simulation period:

$$p_{BF}(t) = p_{BF,FC} + \frac{SWC(t) - SWC_{FC}}{SWC_{max} - SWC_{FC}} \cdot (p_{BF,max} - p_{BF,FC}) \qquad (6.3)$$

where $\mathrm{p_{BF}}$ (t) (-) is the fraction of deep percolation that contributes to baseflow at time step t at which the soil water content is $SWC(t)$ (mm), $\mathrm{p_{BF,FC}}$ is $\mathrm{p_{BF}}$ when the soil water content is at field capacity (SWC_{FC}), and $\mathrm{p_{BF,max}}$ is $\mathrm{p_{BF}}$ when the soil water content is at its maximum simulated value (SWC_{max}). Field capacity was chosen as the lower threshold, as AquaCrop only simulates deep percolation if the soil water content is above field capacity. The $\mathrm{p_{BF}}$

thresholds ($p_{BF,FC}$ and $p_{BF,max}$) were calibrated to the filtered daily baseflow to interflow fraction as a function of the simulated soil water content on that day.

Evaluation of AquaCrop-Hydro's river flow simulation included comparison of simulated and observed cumulative water volumes, total discharge and subflows. Evaluation considered daily time steps, as well as aggregated time steps of 10 days or one month.

Furthermore, AquaCrop-Hydro simulations of seasonal dry crop yield were evaluated against observations of average crop productivity for the period 2000-2013 in the sandy loam region, which covers a large part ($5130\,km^2$) of central Belgium (FOD economie, 2014). Crop yield simulations were evaluated for maize, winter wheat, winter barley, potato, sugar beet, green beans and peas, covering over 70% of the agricultural land of the catchment. Fresh weight yield observations were corrected using typical values of crop's dry matter content at harvest: 25% for potato, 19% for sugar beet, 15% for green beans and 25% for peas (Vanuytrecht, 2013; Steduto et al., 2012; Northolt et al., 2004; Dewaele and Delanote, 2014).

Model evaluation was based on graphical displays as well as the four statistical indicators presented in Box 2.1: R^2, RRMSE and EF and RME.

6.3 Results

6.3.1 Hydrological model parameters

Table 6.3 shows the seven hydrological model parameters as calibrated for the Plankbeek catchment. The calibrated deep percolation parameters resulted in a good match between the observed and simulated baseflow-interflow proportion. Comparison for all days with deep percolation resulted in a high R^2 of 0.86. The recession constants were taken equal to values obtained when applying the WETSPRO filter (Table 6.2).

Table 6.3: Model parameters for AquaCrop-Hydro's lumped conceptual hydrological model.

Parameter		Value
Catchment soil water content at field capacity	SWC_{FC}	650 mm/2m
Maximum catchment soil water content	SWC_{max}	677 mm/2m
Baseflow fraction for soil at field capacity	$\mathrm{p_{BF,FC}}$	0.88
Baseflow fraction for maximum soil water content	$\mathrm{p_{BF,max}}$	0.4
Recession constant baseflow	$\mathrm{k_{BF}}$	35 d
Recession constant interflow	$\mathrm{k_{IF}}$	2 d
Recession constant overland flow	$\mathrm{k_{OF}}$	0.3 d

6.3.2 Model performance

Crop production

Average simulated crop production matched well with the average crop yield reported for the catchment region (Table 6.4). The absolute deviation between observed and simulated yield was not more than 0.4 t/ha, except for maize and winter wheat. Moreover, RRMSE values, summarizing model performance for a year-by-year comparison of simulated and observed yield, ranged between 7% and 37%. Excellent model performance was found for winter barley, while the model performed rather poorly for winter wheat.

Table 6.4: Comparison of observed and simulated average dry crop yield (t dry matter/ha) for the Plankbeek catchment during the period 2000-2013, with corresponding relative root-mean-square error (RRMSE).

Crop	Observed yield (t/ha)		Simulated yield (t/ha)		RRMSE (%)
	average	SD	average	SD	
Maize	11.975	0.621	10.518	0.647	14.9
Winter wheat	8.590	0.582	11.425	1.040	36.5
Winter barley	7.901	0.543	8.160	0.401	7.1
Potato	11.932	1.036	11.753	2.861	23.0
Sugar beet	13.740	1.332	14.126	1.251	12.1
Green beans	1.940	0.208	1.742	0.307	22.4
Peas	1.964	0.202	1.984	0.470	25.4

Soil water balance

Table 6.5 presents the simulated catchment soil water balance for the complete simulation period. About 65% of the rainfall is simulated to leave the catchment as evapotranspiration. The majority of the remaining rainfall (27%) percolates to the groundwater (baseflow) or reaches the river via interflow. Only 7.5% leaves the catchment through surface runoff . Building up of stored water in the catchment during the simulation period is minimal (0.2% of rainfall). The soil water balance was not fully closed, but the error of 9 mm (0.1%) over a period of 15 years was negligible. This error was caused by the fact that AquaCrop output for the soil water balance components is rounded off to one decimal. These rounding off errors accumulated by summing up daily values over the 15-year simulation period.

Table 6.5: Simulated components of the catchment soil water balance for the simulation period 1/1/2000-31/12/2014. Positive and negative values present an inflow and outflow respectively. Water storage includes storage of water in the soil and in surface water reservoirs.

Water component	Flux (mm)	% of rainfall
Rainfall	12776.2	100.0
Evaporation	-4033.4	-31.6
Transpiration	-4347.9	-34.0
Deep percolation	-3457.6	-27.1
Surface runoff	-958.9	-7.5
Net water storage	30.5	0.2
Total	8.9	0.1

Cumulative water volume

The AquaCrop-Hydro model simulates the total cumulative water volume with a small underestimation of about 7% (Table 6.6). As it is clear from Figure 6.3, this underestimation at the end of the simulation period is the result of underestimation during the calibration period (14.5%), which is partly compensated by overestimation during the validation period (12%). Lower overland flow volumes are simulated by the model compared to the filter results (about 24% difference), while the total volume of deep percolation, reaching the outlet via baseflow and interflow, is only lower by about 4%. Furthermore, calibration of the deep percolation parameters (Table 6.3) resulted in good simulations of baseflow (2.5% difference) and interflow volumes (about 10% difference).

Table 6.6: Cumulative water volumes for the evaluation period 6/9/2002-31/12/2014 (400 missing days excluded) with the corresponding relative model error (RME). Values marked with * are observations obtained by the subflow filter. The sum of simulated baseflow and interflow is equal to the simulated deep percolation (DP), while overland flow is equal to simulated surface runoff (RO).

	Observed (mm)	**Simulated (mm)**	**Error (mm)**	**RME (%)**
Total discharge	3509	3266	243	6.9
Baseflow + Interflow (=DP)	2668*	2560	109	4.1
Baseflow	2081*	2029	52	2.5
Interflow	587*	531	56	9.6
Overland flow (=RO)	932*	707	225	24.2

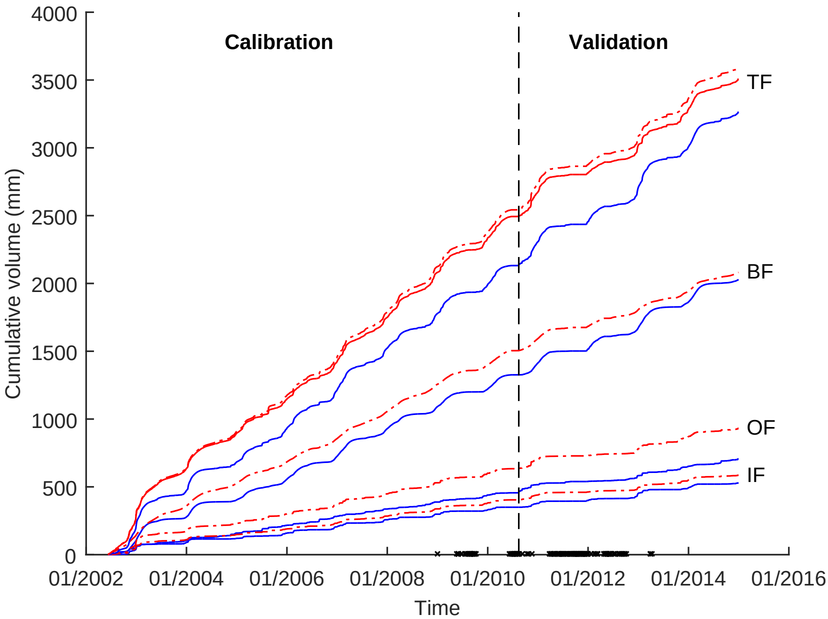


Figure 6.3: Simulated (blue line) and observed or filtered (red line) cumulative water volumes of total discharge (TF), baseflow (BF), interflow (IF) and overland flow (OF) during the evaluation period 6/9/2002-31/12/2014. Full red lines display true observed values, while dashed red lines show values obtained by the subflow filter. Time steps with missing observations, excluded from the cumulative totals for both observations and simulations, are marked on the time axis with x.

Daily discharge

Figure 6.4 shows that AquaCrop-Hydro was capable to simulate the flow dynamics at the catchment outlet. Average daily discharge was simulated with an EF of 0.64 and R^2 of 0.65 for the complete evaluation period (Table 6.7). Performance was slightly better for the calibration period compared to the validation period. Despite the satisfactory simulation of total discharge, statistics reveal unsatisfactory performance for baseflow and overland flow, while the best match between simulation results and filtered subflow were obtained for interflow.

Table 6.7: Performance indicators for simulation of average daily total discharge and corresponding subflows at the outlet of the Plankbeek catchment during the calibration, validation and complete evaluation period. n is the number of days for which model performance was evaluated, R^2 is the coefficient of determination and EF the Nash-Sutcliffe model efficiency.

	Calibration			**Validation**			**Evaluation**		
	n (-)	R^2 (-)	EF (-)	n (-)	R^2 (-)	EF (-)	n (-)	R^2 (-)	EF (-)
Total discharge	2879	0.68	0.66	1310	0.62	0.61	4189	0.65	0.64
Baseflow	2879	0.74	-0.04	1310	0.71	-0.45	4189	0.69	-0.16
Interflow	2879	0.74	0.69	1310	0.63	0.60	4189	0.70	0.65
Overland flow	2879	0.45	0.44	1310	0.50	0.50	4189	0.47	0.47

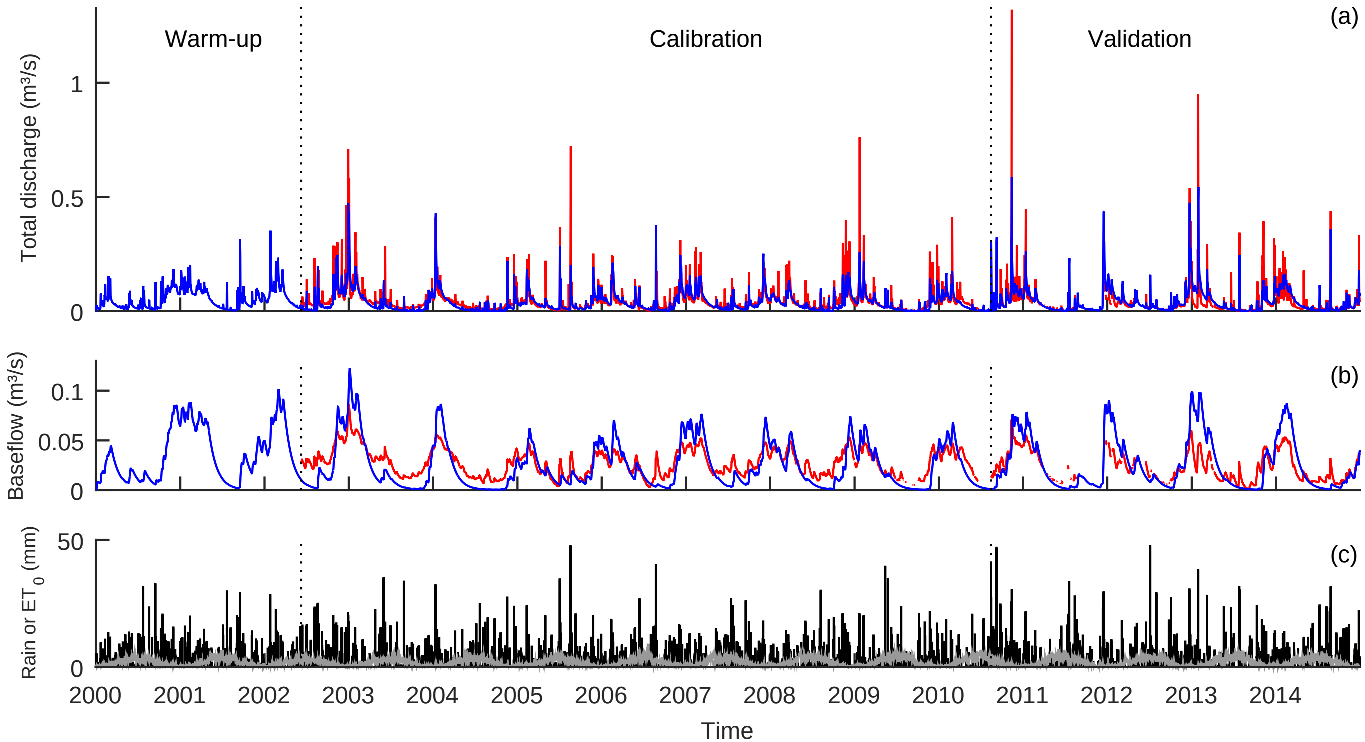


Figure 6.4: Simulated (blue line) and observed or filtered (red line) (a) average daily total discharge and (b) baseflow at the outlet of the Plankbeek catchment together with (c) rainfall (bars) and ET_0 (grey line) for the simulation period 1/1/2000-31/12/2014. Dotted lines separate the simulation period in the warm-up, calibration and validation periods.

The model output error for total discharge can be largely explained by the lower model performance for overland flow, with an efficiency of 0.44 to 0.5; although potential inaccuracies in the structure and application of the subflow filter should be taken into account as well. Figure 6.4 indicates that peak flow events, which are mainly dominated by quick flow processes such as overland flow, were underestimated by AquaCrop-Hydro. Operating at a daily time step, AquaCrop-Hydro neglects the effect of rainfall intensity on surface runoff generation. As shown in Figure 6.5, two similar rainfall events, occurring when the soil was at field capacity, led to simulation of a similar overland flow event. By contrast, the filtered overland flow showed a different response to both rainfall events, most likely because of the differences in rainfall distribution over the day.

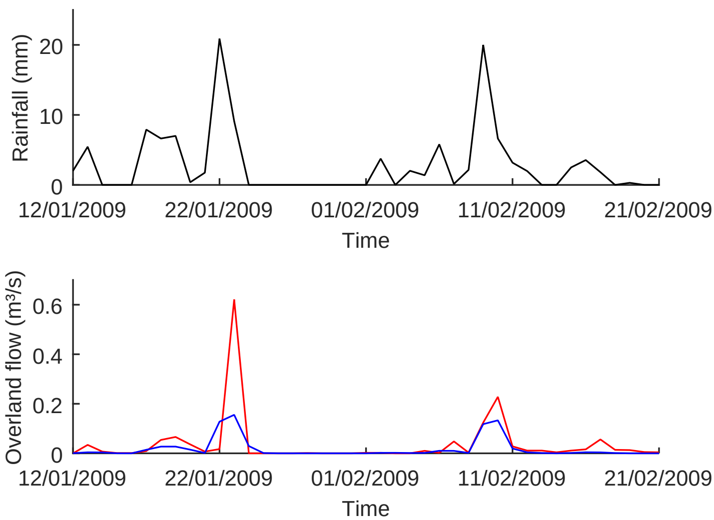


Figure 6.5: Two similar rainfall events (top) result in a similar response of simulated daily overland flow (bottom, blue line), but a different response of average daily filtered overland flow (bottom, red line).

Furthermore, Figure 6.4 indicates that underestimation of total discharge during low flow periods, dominated by baseflow, was another important source of error. Also performance statistics show low model efficiency for baseflow (-0.45 to -0.04), despite the good R^2 values (Table 6.7). Particularly during dry summers in the calibration period (2002-2004, 2008-2009) the underestimation of baseflow was remarkable. During these dry periods, Figure 6.6 shows how simulated deep percolation completely falls to zero as rainfall is insufficient to bring the soil water content above field capacity. By contrast, baseflow observations do present a reaction to rainfall events in summer periods. This could be due to the presence of saturated soils in the catchment, which immediately drain after a rainfall event. However, such events were not considered in the model, as AquaCrop-Hydro was executed with the assumption that there is no shallow groundwater table in the catchment that could saturate soils.

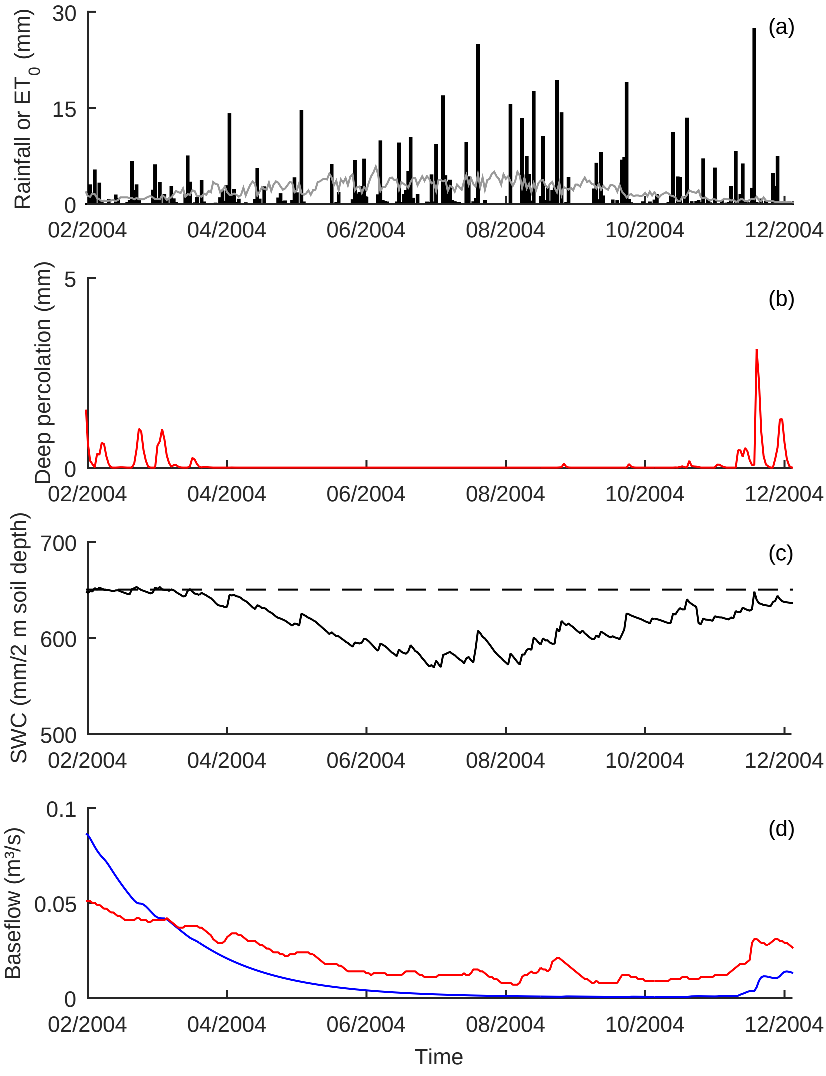


Figure 6.6: (a) Rainfall (bars) and reference evapotranspiration (ET_0) (grey line), with corresponding simulated (b) deep percolation, (c) catchment soil water content (SWC), and (d) resulting observed (red line) versus simulated (blue line) baseflow. Dashed line in c indicates the soil water content at field capacity.

Finally, Figure 6.4 shows that particularly during wet periods in the validation period, baseflow and consequently total discharge were overestimated. This is also reflected by the negative EF value for baseflow during validation (-0.45). The overestimation of baseflow appears to be linked to the underestimation of overland flow during wet periods with intensive rainfall. Since the baseflow overestimation partly compensated the underestimation during the calibration period, the final baseflow volume at the end of the simulation period matched the observed volume well (Table 6.6 and Figure 6.3).

Aggregated flow volumes

Table 6.8 shows that AquaCrop performs better to simulate monthly or 10-day flow volumes as compared to daily discharge. Model efficiency for simulation of total discharge increases from 0.64 at daily basis to 0.82 for 10-day and monthly flow volumes.

Table 6.8: Performance indicators for simulation of average total discharge at the outlet of the Plankbeek catchment during the complete evaluation period 6/9/2002-31/12/2014, when evaluated at daily, 10-day or monthly basis. n is the number of daily, 10-day or monthly periods for which model performance was evaluated, R^2 is the coefficient of determination and EF the Nash-Sutcliffe model efficiency.

	n (-)	**R^2 (-)**	**EF (-)**
Daily total discharge	4189	0.65	0.64
10-day total discharge	436	0.83	0.82
Monthly total discharge	147	0.85	0.82

6.4 Discussion

6.4.1 Model approach and performance

This study shows that AquaCrop-Hydro combines the benefits and functionality of the physically based AquaCrop model and a parsimonious conceptual hydrological model in order to up-scale simulation of water availability from an individual field to a larger agricultural catchment. Thereby, AquaCrop-Hydro tackles many of the limitations of previously developed agro-hydrological models that were identified in Section 6.1.

The major strength of AquaCrop-Hydro is its low requirements for easily obtainable input or calibration data, due to the limited requirements of its two submodels.

AquaCrop, as discussed in Chapter 2, requires a limited amount of input data and parameters, which can be easily obtained from field observations, agricultural statistics or literature (Vanuytrecht et al., 2014a). Furthermore, as illustrated by the above case-study, a user can rely on default soil and management input parameters and predefined crop parameter sets provided in the AquaCrop database and literature.

Next, AquaCrop-Hydro's hydrological submodel only requires time series of river discharge observations to calibrate the hydrological parameters. Such time series are commonly available, even in data-scarce regions, at least for one station (e.g. downstream the catchment) or for a similar catchment nearby. In addition, these time series do not need to cover the complete simulation period, but should be long enough to cover at least some quick and slow runoff events. Furthermore, as the model focuses on estimating water availability, one does not need flow data with very small time resolution. A time step of one day, as considered in this study, would be sufficient. For larger catchments one could even consider larger time steps.

The parsimonious nature of AquaCrop-Hydro is confirmed when comparing its data requirements with those of SWAT, another commonly used crop-centered agro-hydrological model. An exploratory model comparison study in the framework of the REDSIM project (Hunink et al., 2011) states that AquaCrop's data requirements are lower than those of SWAT. A more detailed analysis of input requirements of both models was made in Box 6.1. To simulate the soil water balance, crop growth and production in a single land unit, AquaCrop and SWAT use a similar amount of parameters. The larger amount of parameters required by AquaCrop to simulate processes such as root development and yield formation are caused by increased flexibility for the user to change some settings that are fixed in SWAT. Obviously, the AquaCrop user could also stick to the default values resulting in data requirements equal to those of SWAT. Furthermore, differences in parameter requirements for simulating crop production under water stress (more parameters in AquaCrop) or fertility stress (more parameters in SWAT), are caused by differences in the detail with which the models describe these processes. AquaCrop describes crop responses to soil water stress in more detail, while SWAT is more detailed for analysis of nitrogen and phosphorus fluxes. Also Hunink et al. (2011) assesses AquaCrop's description of the soil water balance and crop growth processes as good, while the description of SWAT is assessed only average. Simulation of irrigation management is even considered poor in SWAT. Finally, it should be noted that not only the number of parameters matters, but also the ease with which these parameters may be obtained. Some of the input parameters required by AquaCrop are easier to determine than those of SWAT (e.g. maximum LAI versus CC_x). Furthermore, the use of both models is highly facilitated by predefined parameter sets available in the models' databases. The SWAT crop database, containing more than 60 different crops, is considerably larger than AquaCrop's database that only contains 14 crops (Table C.1). Especially, grasses and vegetables are much more represented in the SWAT database. By contrast, SWAT does not provide predefined soil parameter sets while AquaCrop does (Table A.1).

Box 6.1: Input requirements of AquaCrop versus SWAT

Input requirements of AquaCrop were compared to those of SWAT for simulation of the soil water content, crop growth, transpiration and production in a single agricultural land unit. Comparison was made for simulation of potential crop growth and production, i.e. only influenced by air temperature and [CO_2], as well as actual crop growth and production, i.e. also affected by water availability and soil fertility stress. Comparison is based on information about the AquaCrop model presented in Chapter 2 and information about the SWAT model provided by Neitsch et al. (2011) and Arnold et al. (2012).

Climate
Both models require input of precipitation, minimum and maximum temperature and additional data to calculate reference evapotranspiration (wind speed, humidity and solar radiation data, depending on the calculation method). While AquaCrop relies on the FAO Penman-Monteith equation, SWAT offers three options for calculation of reference evapotranspiration (e.g. Hargreaves and Samani, Penman-Monteith and Priestly-Taylor). Also solar radiation is a required input for SWAT to simulate crop production, while in AquaCrop this is only optional to be used during ET_0 calculation. Furthermore, SWAT requires input of daily weather data, whereas AquaCrop can interpolate between 10-day or monthly values. However, SWAT includes the option to generate weather data for both historical and future climatic conditions, while AquaCrop does not. Finally, to consider the effect of climate change both models require input of ambient [CO_2] levels.

Soil water balance
Soil physical parameters to describe the soil water retention in each soil layer are very similar. AquaCrop requires 5 soil parameters for each soil layer, whereas SWAT requires 7 (Table C.3). The main difference is that SWAT determines the soil water content at permanent wilting point and field capacity based on input of soil particle distribution, bulk density and available water capacity, while AquaCrop does the opposite by calculating the total available water from input of θ_{FC} and θ_{PWP}. Next to layer specific parameters, both models require 1 additional soil parameter to simulate restriction of root growth. Furthermore, both

models can use the curve number method to simulate surface runoff using 2 parameters (Table C.3), but SWAT also offers the alternative to simulate surface runoff with the Green and Ampt method. Finally, AquaCrop has two soil parameters to simulate capillary rise from a shallow groundwater table into the unsaturated zone. By contrast, SWAT simulates upflow from the groundwater table (‘revap’) as fictive evaporation of groundwater without any interaction with the soil.

Potential root development
SWAT requires only 2 parameters to describe root zone development and root distribution (Table C.2), whereas AquaCrop requires 6 (Table A.2). This is mainly due to the fact that SWAT fixes some of the settings that are specified by the user in AquaCrop. For example, SWAT assumes a linear increase of the rooting depth from 1 cm in the beginning of the season to the maximum depth (RDMX) after 40% of the growing season. AquaCrop on the other hand, allows the user to define the shape of the root expansion function (rtshp), the minimum rooting depth (rtn) and the time to reach the maximum depth (root).

Potential crop canopy development
SWAT requires 9 crop parameters (Table C.2) to describe potential canopy development. Similarly, AquaCrop requires 10 parameters (Table A.2). Both models enable simulation of temperature dependent canopy development using growing degree days. Plant density affecting initial canopy cover (ccs and den) is explicitly defined in AquaCrop, while SWAT assumes a typical rainfed plant density. Description of canopy development is very similar, but SWAT uses leaf area index (LAI) to describe canopy development while AquaCrop uses green canopy cover (CC). It should be noted that CC can be easily determined by visual observation in the field, or by analysing pictures or remote sensing images. By contrast, LAI determination in the field is rather tedious and requires special measuring equipment, while remote sensing images only provide indirect measures for LAI.

Potential crop transpiration
Both models simulate crop transpiration based on potential evapotranspiration and the crop canopy. AquaCrop requires 2 parameters (kcx and kcdcl) to determine the crop transpiration coefficient (Table A.2). By contrast, SWAT uses a fixed constant so that it does not require additional parameters. Only when reference evapotranspiration is calculated by Penman-Monteith 3 additional parametes are required (Table C.2).

Potential crop production
Both models use a very different approach to simulate crop biomass production. SWAT simulates crop biomass based on light interception and radiation use efficiency (RUE), while AquaCrop simulates biomass production from crop transpiration. SWAT requires 8 parameters (11 for trees) to simulate potential crop production, while AquaCrop only requires 4 (Table A.2 and C.2).

To define crop yield from the simulated crop biomass, both models use the harvest index. SWAT only requires 1 parameter to define potential yield, while AquaCrop requires 7 (Table A.2 and C.2). This difference is for example due to the fact that cold and heat stress affect the harvest index in AquaCrop (polmn and polmx), but not in SWAT. Furthermore, SWAT uses a sigmoidal function to describe the increase of the harvest index from zero in the beginning of the growing season to its maximal value (HVSTI) at maturity, while in AquaCrop a user can specify the time when the harvest index starts building up (flo) and reaches its maximum value (hilen).

Actual crop growth and production
Both SWAT and AquaCrop consider the effect of soil fertility and soil water stress on crop growth and production. In AquaCrop water and fertility stress can affect crop biomass production at the same time, while in SWAT only the strongest stress on each day is accounted for.

Under water-stressed conditions, AquaCrop requires 6 additional parameters to simulate canopy development, 3 for transpiration and 5 for yield formation (Table A.2). By contrast, SWAT only requires 1 additional parameter to correct the harvest index for drought (WSYF, Table C.2). Crop transpiration and biomass production are corrected for water stress by comparing the demand for water with the supply of water from the soil profile (potential versus actual water uptake or transpiration). Obviously, the large amount of additional parameters in AquaCrop goes together with a more detailed simulation of the effect of water stress on crop development and production. In AquaCrop, various crop processes have different soil water content thresholds and different shapes of the stress curves. Furthermore, AquaCrop also considers the effect of water logging, while SWAT only considers a crop being stressed because of water shortage.

AquaCrop and SWAT apply a very different approach to consider soil fertility stress. AquaCrop's fertility approach (Chapter 3) is applicable to all nutrients, while SWAT only considers nitrogen and phosphorus. As opposed to SWAT, AquaCrop does not calculate nutrient balances.

Consequently, AquaCrop only requires 4 additional crop parameters to describe crop response to soil fertility stress, while SWAT requires 10. Furthermore, in AquaCrop a user only needs to specify the soil fertility level (B_{rel}), whereas SWAT requires initialization of the soil nutrient status as well as parameters describing (de)nitrification, decomposition, volatilization and mineralization processes. Obviously, the larger data requirements of SWAT go together with a more detailed description of nutrient fluxes in the agro-hydrological system.

Finally, only AquaCrop considers the effect of soil salinity stress, using 7 additional parameters.

Due to the limited data requirements AquaCrop-Hydro is applicable to various agricultural catchments, even in data-scarce regions. This is supported by the fact that AquaCrop has been applied to different cropping systems all around the world (Vanuytrecht et al., 2014a), including data-scarce regions in developing countries like Ethiopia (Abrha et al., 2012; Tsegay et al., 2012), Burkina Faso (Wellens et al., 2013), Iran (Andarzian et al., 2011), Bolivia (Geerts et al., 2009a) and Nepal (Shrestha et al., 2013b). Furthermore, VHM conceptual models were already applied to data-scarce areas in countries such as Ecuador (Mora Serrano, 2013), China (Liu et al., 2011), Uganda (Nyeko-Ogiramoi et al., 2010), Kenya and Ethiopia (Taye et al., 2011). In addition, the generalized hydrological model structure allows flexible adjustment of AquaCrop-Hydro to variable catchment conditions. The interflow component, for example, can easily be discarded if this flow component appears negligible.

Calibration of agro-hydrological models is often challenging. The lack of transparent calibration procedures tends to cause problems to identify parameter values, especially for overparameterized models with strong interaction between different model parameters (Andréassian et al., 2012; Beven, 2006). By contrast, AquaCrop-Hydro contains a limited number of parameters to be calibrated using a transparent guided data-based approach. Being partly physically based, AquaCrop mostly requires parameters that can be observed in the field, rendering calibration unnecessary for most standard applications. Calibration is only necessary when introducing new crops (not included in Table C.1), or when soil fertility or salinity stress is considered (Vanuytrecht et al., 2014a). In those cases, identification of good parameter values is facilitated by the transparent stepwise calculation procedure of the model. In addition, the global sensitivity analysis by Vanuytrecht et al. (2014b) lists priority parameters to which yield output is most sensitive under various environmental conditions, and to which calibration efforts should be directed. The sensitivity analysis showed that under stress-free conditions (no water or temperature stress), accurate specification of biomass water productivity (wp*) is crucial. When water stress is present (but temperature stress absent), soil water retention, root development and crop emergence parameters are very important. By contrast, under conditions of temperature stress (but no water stress), canopy development and cold stress parameters are most sensitive.

Furthermore, AquaCrop-Hydro's hydrological model requires calibration of maximum three recession constants according to the stepwise procedure by Willems (2014). This top-down VHM approach to identify model structure and calibrate the corresponding model parameters avoids the problem of parameter identifiability by matching the model structure to data availability. The model structure is further refined with addition of extra parameters, only when these parameters can be identified from the available data. The procedure is supported by subflow separation using the WETSPRO tool. As both the subflow separation and the VHM conceptual model approach are based on the same linear reservoir concept, recession constants obtained from the WETSPRO filter are expected to be the most optimal values to accurately simulate river discharge. Next to the recession constants, also the p_{BF}-soil water content relation can be calibrated from the filtered subflows. The number of parameters to be calibrated depends on the choice of the relation. It can be only one parameter (constant fraction of baseflow), or just four as presented for the above case study. If necessary, one could opt for higher order equations, although the increase in model performance should be balanced against the extra calibration requirements.

While application of many existing agro-hydrological models is time-consuming with respect to computation time, as well as data handling, input preparation and calibration (Singh and Frevert, 2006), the use of AquaCrop-Hydro is time efficient. The open-access AquaCrop software has a graphical user-interface to process all input, run simulations and visualize model results. In addition, data handling and running simulations for many land units can be facilitated using the AquaGIS and AquaData tools developed by Lorite et al. (2013), or the GeoSim toolbox by Thorp and Bronson (2013). This can especially be useful when running AquaCrop-Hydro for large or heterogeneous catchments with many land units. Furthermore, AquaCrop simulation of a time series of 15 years for the 31 land units took about 2.5 minutes using the AquaCrop plug-in software on a standard computer. Post-processing of AquaCrop simulation results to calculate the catchment soil water balance, as well as simulation of the subflows and total discharge can be conducted in any modelling environment. With a simple Matlab script (Van Gaelen, 2016b) this took only one minute for the Plankbeek catchment. By contrast, execution of the fully distributed process-based nutrient emission model ArcNemo for the same catchment took about 1.5 hour (Van Opstal, personal communication). Moreover, execution times for the semi-distributed SWAT model reported by Yalew et al. (2013) suggest that it could take about 5 to 12 minutes to run a 15-year SWAT simulation for the Plankbeek catchment.

Although conceptual hydrological models have a simple model structure and limited amount of parameters, model comparison has previously shown that more detailed physically based models do not necessarily perform better (Breuer et al., 2009; Refsgaard and Knudsen, 1996; Vansteenkiste et al., 2014). In addition, the performance of AquaCrop is similar to what is reported for other crop models, obviously with variable model comparison results depending on the studied crop and agro-ecological conditions (Abi Saab et al., 2015; Castañeda-Vera et al., 2015; Paredes et al., 2014; Todorovic et al., 2009). Consequently, it is not surprising that AquaCrop-Hydro, despite its simple approach, performed well to simulate crop production and discharge in the study catchment.

Since AquaCrop-Hydro does not take into account crop damage due to diseases and extreme events (e.g. hailstorm), deviations between observed and simulated crop yield are to be expected. Despite these model limitations, crop yield estimations were good, although performance was slightly better in the study by Vanuytrecht et al. (2016), for which the adopted maize, sugar beet and potato crop parameters were calibrated. Moreover, investigation of the simulated discharge at the catchment outlet revealed that AquaCrop-Hydro performed better to simulate total flow at the catchment outlet, as compared to the corresponding subflows. Although evaluation of the subflows is useful to identify the most suitable model structure and parameters, accurate simulation of the subflows is of lesser importance for model application. In the end, the objective was to develop a model that can accurately estimate overall water availability in the catchment (i.e. total flow at the catchment outlet). AquaCrop-Hydro was capable of simulating the cumulative total water volume with a small underestimation of 7% over a period of 13 years. Also, average daily discharge was simulated with a satisfactory accuracy (model efficiency of 0.64) and 10-day and monthly discharges with high accuracy (model efficiency of 0.82). Since a 10-day or monthly time step is sufficiently small to support most decisions regarding water allocation amongst the different users in a catchment, including ecosystem services, domestic water use, agricultural water use for irrigation and industry or hydropower generation, model performance certainly meets the required level for the targeted application domain. Moreover, AquaCrop-Hydro performed as good as the fully distributed ArcNemo model, which was evaluated for the same Plankbeek catchment by Van Opstal et al. (2014). Both ArcNemo and AquaCrop-Hydro simulated monthly discharge with a model efficiency of about 0.82. This clearly illustrates that adopting a semi-distributed approach to simulate the catchment soil water balance in combination with a lumped approach to simulate the river discharge, does not compromise model accuracy, in comparison to a fully distributed approach.

6.4.2 Limitations

The accuracy of AquaCrop-Hydro simulations for the Plankbeek catchment and validity of this study, are determined by limitations of (i) availability and quality of data for input, calibration and evaluation of AquaCrop-Hydro, (ii) assumptions made during model set-up, and (iii) the developed model structure itself.

Data availability was not a key issue for the study catchment. The main limitation for input data was the lack of information on the depth of the groundwater table. This led to the assumption that contribution of capillary rise from a shallow groundwater table to the soil water balance can be neglected. This assumption was not entirely valid. Indeed, the soil map displays poorly drained soils due to the presence of shallow groundwater table for 10% of the catchment, especially in the area next to the river (DOV, 2014). Also, the poor daily baseflow simulations during dry summer periods indicates that the assumption is not entirely true. By contrast, crop transpiration and production simulations are not expected to be affected by neglecting capillary rise as rainfall was already sufficient to assure stress free crop development. It is clear that more accurate information on the depth and temporal variation of the groundwater table for different locations within the catchment could further improve model simulations. Unfortunately, this information is not available. Another option could be to simulate the groundwater table depth based on the baseflow reservoir water content at each time step. However, such a simulation would require additional parameters related to the aquifer porosity and depth, as well as a good estimate of the initial aquifer conditions or a long warming up period. Further research is needed to quantify the potential increase in model performance by implementation of a groundwater simulation module, and weigh this against increased parameter uncertainty and model complexity.

Furthermore, detailed information on the exact crop calendar and observations of crop canopy cover, biomass and yield of fields in the Plankbeek catchment would have been useful to validate the selected crop parameters. However, crop yield simulations matched the observed regional yields well for the tested crops, which cover about 70% of the agricultural area of the Plankbeek catchment. This indicates that lack of field scale validation was not a problem. It is expected that field observations of crop, soil and management characteristics would further improve model simulations. However, such information is rarely available, especially for large catchments. Hence, the current model simulations give a realistic picture of model performance that can be obtained with commonly available data.

In addition to availability, quality of data was particularly crucial during evaluation of AquaCrop-Hydro's simulation of discharge and corresponding subflows against observations. First, discharge observations are subject to measurement errors and derived from water level records using a rating curve that does not consider the effect of riverbed vegetation. Furthermore, the 'observed' subflows were the result of the application of a numerical filter, which depends on subjectively chosen settings. These filter settings were chosen to optimize filter results for the whole time series, balancing over- and underestimations. Consequently, filter values are never perfect. Hence, deviation between simulated and 'observed' values can never be interpreted as merely caused by model errors, but is often the result of several different error sources.

Another limitation was the set-up of the model defining a constant number of LUs, each with a constant relative area over the 15 year simulation period. Data indicated that no drastic changes to land use and cultivated crop rotations occurred in the Plankbeek catchment. Between 2000 and 2014 the cultivated area of each main season crop deviated maximum 6% of the average relative area value that was assigned to the corresponding LUs in this study (VLM, 2014). Although the assumption of constant LUs was clearly reasonable for the study catchment and period, this might not be true in catchments where drastic land use or cropping system changes happen during the simulation period. In those cases, defining LUs with a time variable relative area is expected to improve model performance.

Furthermore, the developed model structure poses some limitations, in particular towards model application. First of all, AquaCrop-Hydro is based on the AquaCrop model. Since AquaCrop was developed for herbaceous crops, it is expected that AquaCrop-Hydro simulations are most accurate for agricultural catchments that are dominated by cropped fields, such as the Plankbeek catchment.

Second, the daily time step of AquaCrop-Hydro affects its performance for simulation of overland flow. It is clear that AquaCrop has its limitations to accurately simulate surface runoff because its daily time step neglects the effect of rainfall intensity on surface runoff generation. This limitation is inherent to the curve number approach, which was originally developed to be event-based (Garen and Moore, 2005; Hawkins et al., 2009), and should be taken into account for model application. Since flood events and peak flows are mainly dominated by overland flow processes, the model should not be used for flood forecasting or design of flood control measures. Flood modelling typically requires model operation at small time steps (hour or 15 minutes). However, such small time steps could not be implemented in AquaCrop-Hydro, as crop models such as AquaCrop are designed to operate with a daily time step. Future research should evaluate whether smaller time steps can be implemented in AquaCrop for surface runoff simulation. This would not only improve overland flow and discharge simulations at catchment scale, but also soil water balance and corresponding crop production simulations at field scale.

Finally, AquaCrop-Hydro's semi-distributed approach to scale up the soil water balance from field to catchment scale brings about some limitations. With the semi-distributed approach, spatial distribution and patterns of land use within the catchment are not considered. Consequently, AquaCrop-Hydro can only be used to assess the quantitative but not the spatial aspect of land use changes. For example, while AquaCrop-Hydro can simulate the effect of increased cultivation of cover crops, it cannot simulate the effect of differences in the spatial location (e.g. in the upstream versus downstream part of the catchment) of these cover crops.

6.4.3 Implications

Once calibrated to a specific agricultural catchment, AquaCrop-Hydro can be applied to support sustainable water management in that catchment. Due to its physically based soil water balance model and yield simulation, AquaCrop-Hydro can assess the effect of various agricultural management practices. Since management options can be evaluated from field to catchment scale, their water productivity enhancing effect can be optimized at field scale, while controlling their large scale impact on water availability in the catchment. In addition, AquaCrop-Hydro accounts for the impact of climate change. Simulation of crop development, transpiration and biomass production is adapted to changing CO_2 concentrations and future weather conditions (Subsection 2.5.3), as well as to potential management adaptation strategies (Section 2.6). Consequently, also the catchment soil water balance and discharge are adjusted to future climatic conditions. This is an important advantage over conceptual hydrological models, which usually apply a static equation relating evapotranspiration to the soil water content and climatic conditions, neglecting vegetation feedbacks to the hydrological system. Also, physically based hydrological models do not always accurately consider the dynamic nature of crop development and transpiration under future climatic conditions and CO_2 levels (Gassman et al., 2007; van Walsum and Supit, 2012). It is expected that the accuracy of climate change impact assessments will improve by using a dynamic approach such as implemented in AquaCrop-Hydro.

6.5 Conclusion

The AquaCrop-Hydro model presented in this study is a parsimonious and widely applicable agro-hydrological model, developed based on the crop simulation model AquaCrop and a VHM conceptual hydrological model. Next to simulation of crop production and crop water productivity at field scale, AquaCrop-Hydro simulates the catchment soil water balance applying a semi-distributed approach. In addition, river discharge at the catchment outlet is simulated using a lumped conceptual hydrological model. Being partly physically based, the model can simulate the effect of management and environmental changes on crop production and catchment hydrology. This study demonstrates that AquaCrop-Hydro requires a limited amount of data and parameter calibration, but performs well to simulate crop yield and discharge at the catchment outlet. Therefore, AquaCrop-Hydro can be used to support water management decisions in agricultural catchments, especially in data-scarce regions.

Chapter 7

Assessing the agro-hydrological impact of climate and agricultural management changes using AquaCrop-Hydro

7.1 Introduction

The AquaCrop-Hydro model was developed to fill the need for a parsimonious agro-hydrological model that can be used to study the impact of agronomic and environmental changes on both crop productivity and catchment hydrology. Model evaluation in Chapter 6 showed that AquaCrop-Hydro performed well to simulate crop productivity and discharge at the catchment outlet of an agricultural catchment in Belgium.

Because of its process-based nature and parsimonious nature, AquaCrop-Hydro appears to have some advantages over other agro-hydrological models when applied to study the agro-hydrological impact of climate or agronomic management changes. Unlike conceptual hydrological models, AquaCrop-Hydro can simulate the effect of agricultural management on catchment hydrology. In addition, the effect of climate change is simulated more dynamically as its effect on crop growth and transpiration is taken into consideration for simulation of the soil water balance. Furthermore, AquaCrop-Hydro has relatively low computational requirements. This is especially useful for climate change impact assessment, which typically requires a large number of simulations for a large ensemble of climate scenarios to consider the high uncertainty in future climate projections generated by climate models (Collins, 2007).

Yet, these advantages for agro-hydrological impact assessment have never been demonstrated. For that reason, this study evaluates the use of AquaCrop-Hydro for investigation of the impact of climatic and agronomic management changes on crop development and crop productivity as well as catchment hydrology for an agricultural catchment in Belgium.

7.2 Methodology

7.2.1 Study area

The catchment of the Plankbeek stream, located in the sandy loam region of Flanders (Belgium), covers an area of 4.5 km^2 and ranges in altitude between 17 and 70 m a.s.l. On the silt loam to sandy loam soils of the catchment, agricultural land use dominates (94% of catchment area). In addition to grassland (18% of agricultural land), the most prevalent crops are winter wheat (20%), potato (16%), maize (14%), sugar beet (11%) and peas (6%) (AGIV, 2014, 2001; VLM, 2014). The area is characterised by a temperate climate with mild winters and cool summers, with rainfall uniformly spread over the year. More details on the study area are presented in Chapter 6.

7.2.2 The AquaCrop-Hydro model

The agro-hydrological model AquaCrop-Hydro was developed as a combination of the AquaCrop crop water productivity model (Hsiao et al., 2009; Steduto et al., 2009; Raes et al., 2009; Vanuytrecht et al., 2014a) and a lumped conceptual hydrological model per the generalized structure by Willems et al. (2014). AquaCrop-Hydro simulates the daily soil water balance, crop development and production, based on limited inputs of climate data (daily rainfall, reference evapotranspiration, minimum and maximum temperature and global average annual CO_2 concentration), crop characteristics (e.g. sowing date, length of the growing period, harvest index, rooting depth, sensitivity to abiotic stresses), soil and groundwater table characteristics (soil water retention characteristics and saturated hydraulic conductivity, groundwater table depth), and agricultural management practices for each land unit of the catchment. Based on few hydrological parameters, including three recession constants and parameters determining the baseflow-soil water content relation, AquaCrop-Hydro enables simulation of daily discharge at the catchment outlet.

The AquaCrop-Hydro model was calibrated and validated for the Plankbeek catchment based on seasonal crop yield and daily discharge observations at the catchment outlet for the period 2000-2014 (Chapter 6). It was assumed that the validated hydrological model parameters (Table 6.3), representing the catchment hydrological response behaviour, remain valid for future climatic conditions and adapted agronomic management practices. A more detailed description of the AquaCrop-Hydro model and its application to the Plankbeek catchment can be found in Chapter 6.

7.2.3 Climate change impact analysis

The agro-hydrological impact of climate change in the study catchment was studied by comparing simulations of crop development and production as well as catchment water availability for historical weather conditions to simulations for the weather conditions of the year 2050 under RCP (Representative Concentration Pathway) 8.5. The RCP 8.5 scenario corresponds to the most extreme scenario of climate change in which greenhouse gas emissions keep on increasing throughout the 21st century (Meinshausen et al., 2011).

Historical climate data

A 30 year baseline period from 1985 to 2014 was selected to represent the natural multi-decadal climatic variability of Belgium (Willems, 2013a,b). Daily weather observations for the baseline period were obtained from meteorological stations of the Royal Meteorological Institute (KMI) located near the catchment. Average catchment rainfall was based on rainfall records of the station of Kruishoutem (50°56'N, 3°31'E, 9 m a.s.l.) and Oudenaarde (50°51'N, 3°37'E, 14 m a.s.l.) using the Thiessen polygon method. Daily minimum and maximum temperature (T_{min} and T_{max}) recorded at the station of Semmerzake (50°56'N, 3°40'E, 37 m a.s.l.) were used. Reference evapotranspiration (ET_0) was calculated with the FAO Penman-Monteith method using daily data from the station of Semmerzake (T_{min} and T_{max}, minimum and maximum relative humidity, average wind speed, sunshine hours) supplemented with measurements of sunshine hours at the station of Melle (50°59'N, 3°49'E, 15 m a.s.l). The average annual CO_2 concentration ([CO_2]) for the baseline period was kept constant at 369.4 ppm, i.e. the observed level at the Mauna Loa Observatory in Hawaii for the mid-period year 2000.

Future climate data

Future daily weather data were generated using the climate perturbation tool version 2016 (Van Uytven and Willems, 2016), which was specifically developed for Belgium. This tool generates future weather data on the basis of historical data using perturbation factors. The tool derives these perturbation factors by statistical downscaling of general circulation models (GCMs) results. Based on historical weather data for the 30 year baseline period, 30 sets of weather data representative for 2050 under RCP 8.5 were generated according to seven GCMs (Table 7.1). Input and generated weather parameters consisted of rainfal, T_{min}, T_{max} and ET_0. The quantile perturbation method by Ntegeka et al. (2014) was selected for rainfall perturbation, while the mean delta change method (Willems et al., 2012) was selected for perturbation of ET_0, T_{min} and T_{max}. All selected

GCMs originated from the Coupled Model Intercomparison project Phase 5 (CMIP5) (Taylor et al., 2012) and have a resolution of about 1.4°. GCMs results were extracted by Tabari et al. (2015b) for central Belgium (Uccle). The ensemble composition was inevitably based on the availability of GCM results for all four required weather parameters. Moreover, the ensemble was composed so that its rainfall perturbation factors did not drastically deviate from to the expected trend for Flanders (Tabari et al., 2015b).

Although using an ensemble with a limited number of GCMs reduces time and computation requirements for the impact assessment, it might result in a biased representation of the uncertainty of climate change impacts. For that reason, sensitivity of the simulated impact to the selected ensemble was investigated by repeating the climate change impact assessment using synthesized scenarios. Synthesized scenarios summarize the full range of available climate model projections in a limited number of representative future climate scenarios. This reduces the number of impact model simulations, while capturing the variability between various climate projections. Although the development and use of synthesized scenarios is well established to study the hydrological impact of climate change, it is unclear whether this approach is also applicable to study climate change impact on agricultural production. For that reason, both the ensemble and synthesized scenario approach, each with their own strengths and limitations, were compared to simulate the agro-hydrological impact of climate change in the study area.

Future daily weather data according to four synthesized scenarios were generated with the same climate perturbation tool (Van Uytven and Willems, 2016). The four synthesized scenarios were developed by Ntegeka et al. (2014) according to their expected hydrological impact: high summer impact, high winter impact, mean impact and low impact on river discharge. During scenario generation, the impact of an extensive set of climate projections on river discharge at the outlet of a catchment in central Belgium was analyzed using a VHM lumped conceptual model. By grouping these hydrological impact simulations and back-tracing them to the corresponding climate signals, the extensive set of climate projections was reduced to four representative scenarios. Figure B.1 to Figure B.3 present the signals underlying the synthesized scenarios (48 GCM signals for rainfall, 9 signals for ET_0, 9 signals for T_{min} and 10 signals for T_{max}). These signals also include the seven GCMs signals selected for the ensemble (Table 7.1).

[CO_2] for 2050 was set to 541 ppm according to the RCP 8.5 projections (Meinshausen et al., 2011) for both the ensemble and synthesized scenarios.

Table 7.1: General circulation models from the the Coupled Model Intercomparison project Phase 5 (CMIP5) used for generating future weather data for the Plankbeek catchment.

Research centre	**Climate model**
Centre National de Recherches Meteorologiques	CNRM-CM5
Geophysical Fluid Dynamics Lab	GFDL-CM3
	GFDL-ESM2G
	GFDL-ESM2M
Institut Pierre-Simon Laplace	IPSL-CM5A-LR
	IPSL-CM5A-MR
Meteorological Research Institute	MRI-CGCM3

Crop response to climate change

Crop development and production are likely to be affected by climatic changes as crops respond to changes in available soil water, as well as air temperature and [CO_2]. The AquaCrop simulation procedures to simulate crop responses to these abiotic factors are discussed in more detail in Section 2.5. Table 7.2 summarizes crop parameters that determine the magnitude of crop responses to temperature and [CO_2] for each of the simulated crops of the Plankbeek catchment.

Since AquaCrop was ran in growing degree day (GDD) mode for most crops, the timing and length of the growing stages was adapted to air temperature on the basis of the crops' temperature thresholds (tb and tup). Moreover, biomass production reached its full capacity once the GDD threshold (stbio) was exceeded. By means of the sink term (f_{sink}) the biomass water productivity (wp*) was also adjusted to elevated [CO_2]. The sink term parameters were either chosen equal to those used in the Belgian case-study by Vanuytrecht et al. (2016), or selected within the ranges presented by Vanuytrecht et al. (2011). In addition, pollination started to fail when temperature exceeded the minimum or maximum threshold (polmn and polmx). The latter was only applicable to crops that require pollination, excluding root vegetables and legumes.

Finally, crop canopy development and production were affected by water stress (drought or aeration stress) when water in the root zone exceeded process-specific thresholds. The complete set of crop parameters, including those determining crop responses to water stress, are presented in Table B.3.

Table 7.2: Overview of simulated crops with crop parameters that determine crop response to temperature and [CO_2]. Presented crop parameters include the base (tb) and upper temperature (tup) beyond which crop development does not further progress, minimum (polmn) and maximum (polmx) air temperature below or above which pollination starts to fail, minimum growing degree days required for full biomass production (stbio), and the crop performance under elevated [CO_2] levels (f_{sink}). The complete set of crop parameters is presented in Table B.3.

	Temperature response					[CO_2] response
Crop	**tb** (°C)	**tup** (°C)	**polmn** (°C)	**polmx** (°C)	**stbio** (°C/d)	$\mathbf{f_{sink}}$ (%)
Winter wheat	2	26	5	35	8	0
Winter barley	0	15	5	35	8	0
Maize	8	30	10	40	13	0
Sugar beet	5	30	8	40	9	50
Potato	2	26	-	-	8	75
Green beans	6	30	-	-	14	60
Peas	0	30	-	-	14	60
Carrot	2	26	-	-	8	60
Grassland	2	40	8	40	13	50
Deciduous forest	10	30	10	40	-	50

7.2.4 Agricultural management impact analysis

Alterations in timing of cultivation, including planting and maturity date, are one of the most obvious crop management adaptation strategies in response to changing weather conditions. It is expected that in the future, spring-sown crops ('spring crops') will be planted earlier to avoid hot and dry periods in summer and benefit more from winter rainfall (Olesen et al., 2011). Due to warmer temperatures, also winter sown crops ('winter crops') could be sown earlier so that a strong crop is established before winter. On the other hand, sowing might be delayed as the low temperatures required for vernalization occur later in the year. Moreover, sowing too early could lead to the crop being in a stage more susceptible to frost damage during winter (Olesen et al., 2012). Furthermore, because of the higher temperatures and potential advances of planting dates, crop varieties with a longer growing cycle can be cultivated. However, these late maturing varieties are only suitable when their cycle does not interfere with the rotation cycle. Moreover, they will only thrive well when not affected by limited water availability in summer. To limit extra water stress during summer, farmers could implement additional field management practices such as mulching or tied ridges.

The adapted planting dates (Table 7.3) for maize, sugar beet, potato and deciduous trees in the Plankbeek catchment were either calculated based on the projected future spring temperatures and reported historical temperature dependent planting date changes for Europe (Chmielewski et al., 2004; Chmielewski and Rötzer, 2001; Estrella et al., 2007), or based on temperature dependent modelling of future planting dates (Vitasse et al., 2011). Although the obtained planting date adaptations varied due to different temperature criteria and different spring temperature projections for different GCMs and years, a single planting date for all future simulations was selected for each crop. Sowing dates of winter wheat and winter barley could have been advanced according the historical trends reported by Estrella et al. (2007), but were left unchanged for this study after the example by Olesen et al. (2012) because of the unknown balance of potential positive and negative effects to early sowing.

The growing cycle of deciduous trees was extended so that the end of leaf abscission occured at the same date (31 October) as for historical conditions. Also historical observations show that the growing cycle length slightly increased and partly compensated for the advance of the growing cycle due to earlier leaf sprouting (Chmielewski and Rötzer, 2001; Vitasse et al., 2011). Similarly, for all other spring and winter crops the extension of growing cycle was set to the median growing degree days required under future climatic conditions to obtain the median actual historical maturity date. The extension of the growing cycle was obtained by extending the mid-season yield formation period right before senescence. Due to lack of information for vegetable crops, the growing cycle was adapted similar to adaptations for other spring crops. Finally, the growing cycle of grassland was kept unaltered, as it already stretches the complete year in most cases.

Adapted field surface practices, including a 50% cover of organic mulches and tied ridges, were simulated for all spring crops. On the one hand, these practices conserve water and can counter the expected water stress. On the other hand, the selected practices are in accordance with the soil erosion reduction measures, enforced since January 2016 by the Flemish government as cross compliances for agriculture subsidies for cultivation on fields with a strong susceptibility to erosion (LV Vlaanderen, 2016). In the Plankbeek catchment, 10% of the fields have a strong susceptibility to erosion (DOV, 2016), and need to implement these erosion reduction measures. Moreover, as about 45% percent of the catchment consists of soils that are medium prone to erosion, it is very likely that by 2050 farmers have adopted such erosion control measures on all their fields. By contrast, adapted field surface practices were not considered on fields with crops that are less prone to erosion, such as winter cereals and crops providing permanent cover (grassland).

Table 7.3: Planting date, growing cycle length (in calendar days (d) or growing degree days (GDD)) and field surface practices under traditional and adapted management. Organic mulches with a cover of 50% reduce soil evaporation by 25% throughout the growing season, whereas tied ridges impede surface runoff.

	Traditional management			**Adapted management**		
Crop	**Planting or regrowth***	**Growing cycle length**	**Field surface practices**	**Planting or regrowth***	**Growing cycle length**	**Field surface practices**
Winter wheat	25 Oct	1900 GDD	-	25 Oct	1994 GDD	-
Winter barley	1 Oct	1900 GDD	-	1 Oct	1966 GDD	-
Maize	25 Apr	1200 GDD	-	18 Apr	1314 GDD	Mulches
Sugar beet	15 Apr	1850 GDD	-	8 Apr	1989 GDD	Mulches
Potato	25 Apr	1850 GDD	-	15 Apr	1868 GDD	Tied ridges
Green beans	1 Jun	870 GDD	-	25 May	898 GDD	Mulches
Peas	1 Apr	945 GDD	-	25 Mar	995 GDD	Mulches
Carrot	15 May	1850 GDD	-	8 May	1933 GDD	Tied ridges
Grassland	15 Mar	215-365 d**	-	15 Mar	215-365 d**	-
Deciduous forest	10 Apr	205 d	-	1 Apr	214 d	-

* Sowing or planting for annual crops, regrowth for perennials

** Growing cycle length varies depending on the temporary or permanent character of the grassland

7.2.5 Impact analysis

The magnitude of climate change was analysed by assessing changes to median annual and monthly weather variables including average minimum and maximum temperature, total rainfall, total evapotranspiration, and the aridity index (AI). The latter is the ratio of total rainfall to reference evapotranspiration.

The impact of climate change and related management adaptation strategies on water availability was studied by assessing total discharge at the catchment outlet on a yearly or monthly basis. In addition, the impact on different subflow fractions, i.e. baseflow, interflow and overland flow, was assessed. Furthermore, changes to contributions of different components to the catchment soil water balance were assessed.

The catchment's vegetation response to climate and management changes was studied by means of the catchment's evapotranspiration coefficient ($\mathrm{K_{ET}}$):

$$K_{ET} = \frac{E_{act} + Tr_{act}}{ET_0} \tag{7.1}$$

where $\mathrm{K_{ET}}$ is the catchment evapotranspiration coefficient (mm/mm) and Tr_{act} and E_{act} are the catchment actual crop transpiration and soil evaporation (mm) as determined by Equation 6.1. The simulated Tr_{act} and E_{act} have been adjusted to the soil water content and climatic conditions as shown by Equation 2.1 and 2.9.

The impact of climate and management changes on crop development and production was evaluated for the five most important crops of the catchment, i.e. winter wheat, potato, maize, sugar beet and peas, which cover together almost 70% of the total agricultural area. Crop variables were averaged over all land units with the same crop, that differed in soil type or soil cover outside the main growing season. The impact on crop development and production was evaluated by analysing crop yield (Y), ET crop water productivity (WP_{ET}) and the length of the growing period (LGP). The length of the growing period, being the time between crop germination and maturity, is not just determined by temperature and the crops' GDD requirements (Table 7.3) but is also affected by stresses causing early senescence. Furthermore, water and temperature stress affecting crop production were evaluated by means of three stress indices: (i) the cold stress index (CSI):

$$CSI = \frac{\sum_{i=1}^{LGP}(1 - Ks_{b,i})}{LGP} \cdot 100 = \frac{B_{pot,c0} - B_{act}}{B_{pot,c0}} \cdot 100 \tag{7.2}$$

where CSI is the cold stress index (%) or seasonal average of cold stress affecting crop biomass production, $\mathrm{Ks}_{b,i}$ is the temperature stress coefficient for biomass production (Equation 2.2) on day i of a growing period with LGP number of days, B_{act} is the actual seasonal biomass production as affected by various stresses (t/ha), and $B_{pot,c0}$ is the potential seasonal biomass production when no cold stress would have occurred (t/ha) for the same cropping system.

(ii) the heat stress index (HSI):

$$HSI = \frac{Y_{pot,h0} - Y_{act}}{Y_{pot,h0}} \cdot 100 \qquad (7.3)$$

where HSI is the heat stress index (%) that quantifies the relative yield loss because of heat stress affecting pollination, Y_{act} is the actual seasonal yield production as affected by various stresses (t/ha), and $Y_{pot,h0}$ is the potential yield production when no heat stress would have occurred (t/ha) for the same cropping system.

(iii) the water stress index (WSI):

$$WSI = \frac{B_{pot,w0} - B_{act}}{B_{pot,w0}} \cdot 100 \qquad (7.4)$$

where WSI is the water stress index (%) that quantifies the relative biomass loss due to water stress (both shortage and excess of water), B_{act} is the actual seasonal biomass production as affected by various stresses (t/ha), and $B_{pot,w0}$ is the potential seasonal biomass production when no water stress would have occurred (t/ha) for the same cropping system.

In addition to the analysis of the climate change and management impact on median crop and flow variables, changes to inter-annual variation were visualized by means of cumulative distribution function (CDF) plots and quantified by means of the range between the highest and lowest value. Moreover, inter-ensemble variation was presented either by displaying impact results for all GCMs, or by means of boxplots. Each boxplot displayed the 25% and 75% percentile of the ensemble as the box borders, with the ensemble median as the centre line of the box. The whiskers extended 1.5 times the interquartile range above and below the box, while outliers exceeding this range were presented by means of plus signs. For an odd number of data points, the 25% and 75% percentiles were derived by linear interpolation between the data points with closest percentile values.

7.3 Results

The impact of climate change and related management adaptations on weather conditions, water availability, crop production and crop development in the Plankbeek catchment will be discussed and compared to the simulated historical conditions. First, climate and management impact will be studied using an ensemble approach. After, these results will be compared to the climate change impact as simulated using the synthesized climate scenarios.

7.3.1 Climate change and agricultural management impact under the ensemble approach

Weather conditions

Table 7.4 presents expected changes to median annual weather conditions as projected by the ensemble of GCMs. Median monthly weather conditions for each GCM as compared to the historical conditions are presented in Figure 7.1. Projected weather conditions for the synthesized scenarios are discussed in Subsection 7.3.2.

The ensemble of seven GCMs projected an increase of both minimum and maximum temperature by 2050. With a median increase by 1.1 to 2.8 °C, the annual average maximum temperature increased slightly more than the annual average minimum temperature which increased by 1 to 2.5 °C. Figure 7.1 shows that temperature increase was strongest in summer months. Annual average ET_0 was projected to rise by up to 16.5% (113 mm/y). As for temperature, strongest ET_0 increases were found during the summer months. On a yearly basis the majority of GCMs also predicted an increase of rainfall, by up to 10.4% (88 mm/y). While all projections agree on an increase of winter rainfall, not all agree on summer rainfall. Two of the seven GCMs even predicted an increase of summer rainfall as depicted in Figure 7.1. Due to the projected increase in winter rainfall combined with a mild increase of ET_0, winters are predicted to be more humid by all GCMs (AI increases). By contrast, the majority of the GCMs predict more arid summers (decrease of AI) due to the strong increase of ET_0 combined with decreasing rainfall. Due to the more arid summers the majority of GCMs also predicted more arid weather when evaluated on a yearly basis, with a decrease of AI by up to 0.16.

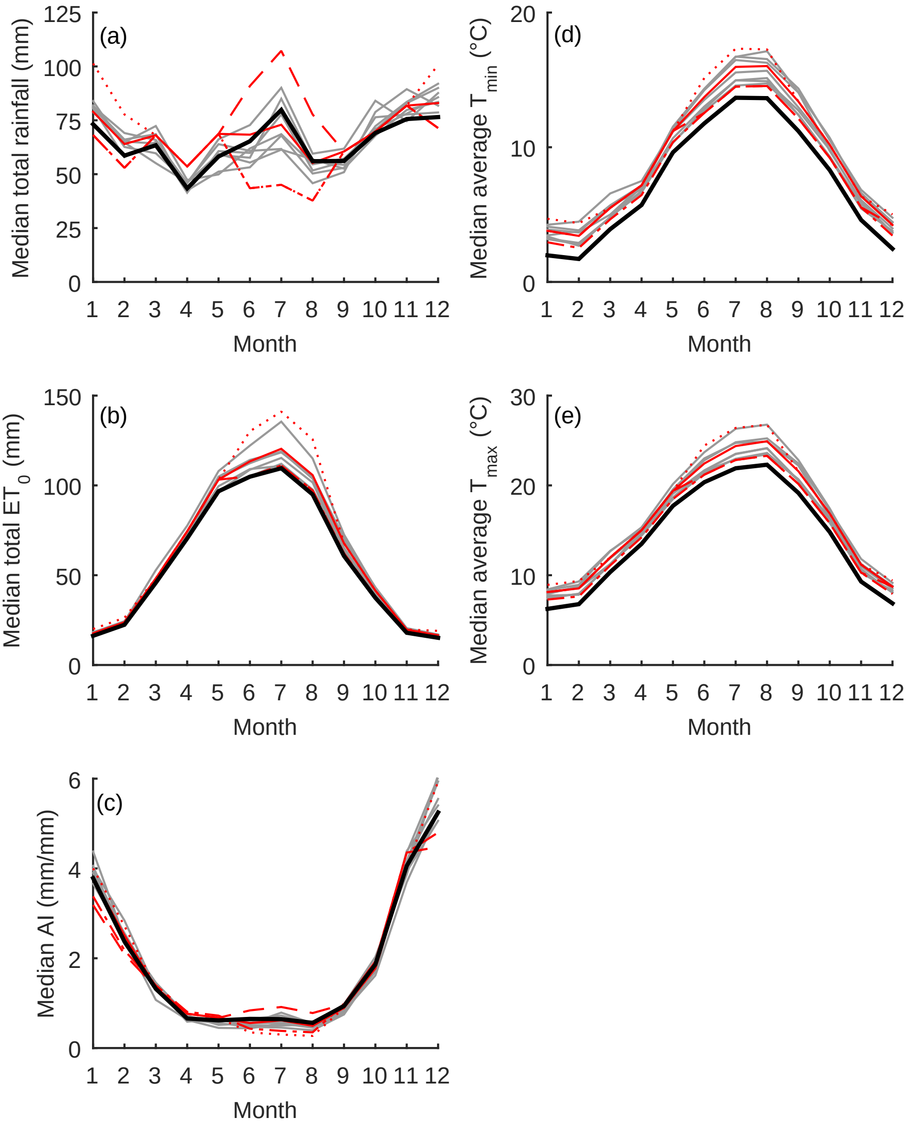


Figure 7.1: Median (a) total monthly rainfall, (b) total monthly reference evapotranspiration (ET_0), monthly aridity index (AI), (d) monthly average minimum temperature (T_{min}) and (e) monthly average maximum temperature (T_{max}) in the Plankbeek catchment for historical climate of 1985-2014 (black) and future climate of 2050 as projected by seven GCMs (grey) and 4 synthesized scenarios (red). The synthesized scenarios correspond to high summer impact (Hs, dashed red line), high winter impact (Hw, dotted red line), mean impact (M, full red line) and low impact (L, dash-dot red line).

Table 7.4: Changes in median annual weather conditions in 2050 as compared to historical weather conditions (1985-2014) for the Plankbeek catchment. The annual aridity index (AI) is the ratio of total annual rainfall over total annual ET_0. Presented range (minimum, median and maximum) for future median changes represent the variety between the median values of each of the seven GCMs of the ensemble. A positive change value represents an increase, while a negative value represents a decrease.

Annual weather parameter		**Historical median**	**Future median change minimum**	**Future median change median**	**Future median change maximum**
Total ET_0	(mm/y)	693	+13	+51	+113
Total rainfall	(mm/y)	840	-9	+14	+88
AI	(mm y/mm y)	1.20	-0.16	-0.04	+0.02
Average T_{min}	(°C)	7.4	+1.0	+1.8	+2.5
Average T_{max}	(°C)	14.1	+1.1	+1.6	+2.8

Catchment water availability

Future annual flow with corresponding subflows is compared to historical conditions in Figure 7.2 and Figure 7.3. While Figure 7.2 focuses on presenting variability between the different GCMs of the ensemble and both management scenarios, Figure 7.3 also displays inter-annual flow variability. Inter-annual variability is also quantified by means of the flow range (Table 7.5). To complement these visual representations, Table B.6 lists the exact median annual flow values under historical and future conditions.

Water availability, represented by the median annual total flow at the catchment outlet, increased under future conditions by 4% to 27%. Figure 7.2 shows that under traditional crop management this increase of total flow (median of 11%) was caused by an increase of each of the subflows. Median overland flow increased relatively more (12.5%) than interflow (8%) and baseflow (6%). However, in absolute terms median baseflow and overland flow increases were almost equal (about 10 mm/y). Although variation between different GCMs was rather large, all GCMs pointed towards an increasing flow trend. Only for baseflow and interflow some of the GCMs predicted a small decrease of up to -1% and -6% respectively.

On a yearly basis, management adaptations barely affected total flow (Figure 7.2). By contrast, the relative contributions to the total flow seriously shifted under adapted management as compared to traditional management. Overland flow strongly reduced (about 20%) due to implementation of adapted management practices such as tied ridges, while interflow and baseflow increased by 3% and 8% respectively.

Furthermore, apart from median flow also inter-annual flow variability was affected by future conditions (Figure 7.3 and Table 7.5). With the exception of interflow, flow variability increased under future climatic conditions. Especially, overland flow became more variable, with a median flow range increase by almost 20%. Introduction of adapted management, further increased inter-annual variability for baseflow and interflow, but decreased variability for total flow and overland flow as compared to traditional management.

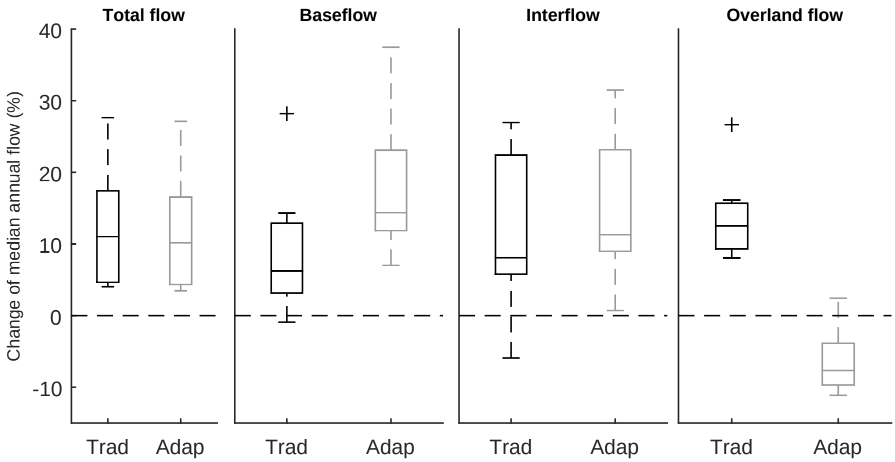


Figure 7.2: Changes of median annual total flow and subflows in 2050 for the Plankbeek catchment under traditional management (black) and adapted management (grey) with reference to historical conditions (1985-2014). A positive change value represents an increase, while a negative value represents a decrease of annual flow as compared to historical conditions. Boxplots present the variation of the median annual flow change between seven GCMs.

Table 7.5: Flow range in 2050 for the Plankbeek catchment under traditional and adapted management as compared to historical conditions (1985-2014). The flow range represents the difference between the maximum and minimum of all annual flow values (n=30). The flow range for future conditions is the median flow range of the seven GCMs. Values between brackets represent the relative change as compared to historical conditions.

	Historical range (mm/y)	**Future range** (mm/y)			
		Traditional management		**Adapted management**	
Annual total discharge	298	307	(+2.9%)	303	(+1.5%)
Annual baseflow	183	184	(+0.4%)	190	(+3.8%)
Annual interflow	69	68	(-0.6%)	69	(+0.6%)
Annual overland flow	73	87	(+19.6%)	67	(-8.1%)

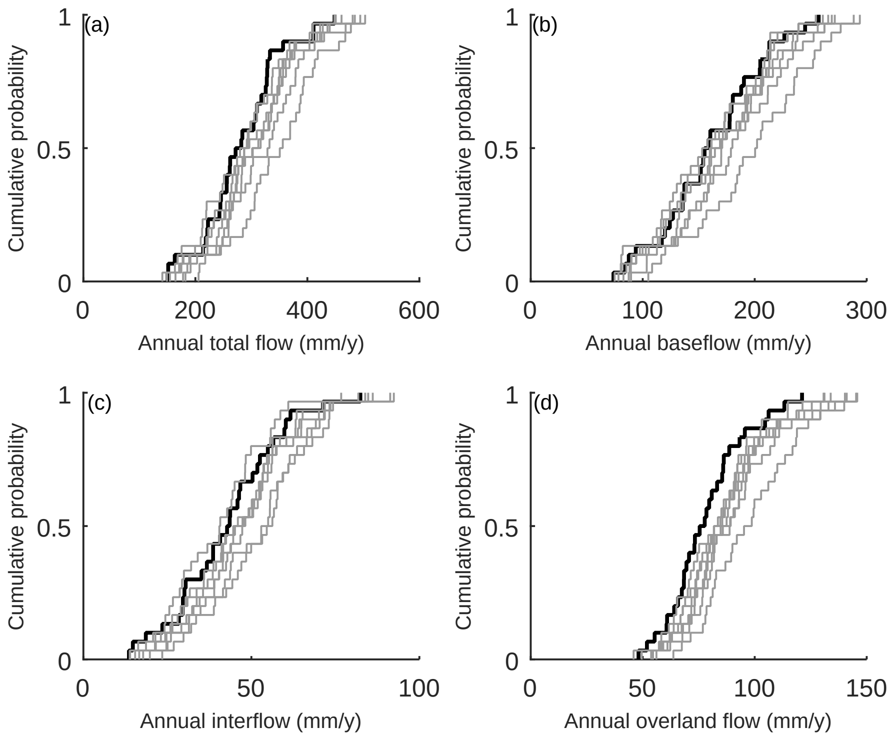


Figure 7.3: Cumulative probability distribution for annual (a) total flow, (b) baseflow, (c) interflow and (d) overland flow under traditional agricultural management in 2050 according to seven GCMs (grey) as compared to historical conditions (1985-2014) (black). Probabilities were based on 30 seasonal values for the baseline period 1985-2014, and 30 seasonal values for 2050 for each GCM.

Although annual total flow increased for future conditions, this increase of flow is not necessarily spread evenly over the year. To zoom in on seasonal flow changes, Figure 7.4 displays changes to the median monthly total flow.

Changes to total flow as a response to climate change followed the observed weather trends, indicating more arid summers and wetter winters. Median monthly total flow increased during late fall to early spring (November to May), and decreased during summer and beginning of fall. However, Figure 7.4 shows large variation between different GCMs. Especially during summer and fall months, for which the GCMs did not even agree whether flow would decrease or increase. Under traditional management, the median total flow decreased in summer and fall, but some GCMs predicted an increase of total flow.

Adapted management did not affect median monthly flow much during winter and early spring months. Between December and April, the difference between both management strategies for median monthly flow was maximum 6%. By contrast, considering management adaptations makes a large difference in flow predictions (up to 12%) for late spring, summer and fall, which corresponds to the growing season of most crops in the catchment. During the main growing season, adapted management increased flow as compared to traditional management. Consequently, the increase of flow in late spring became stronger, while the decrease of flow during summer was counteracted. Only in August adapted management seemed to slightly enforce the decrease of median monthly flow.

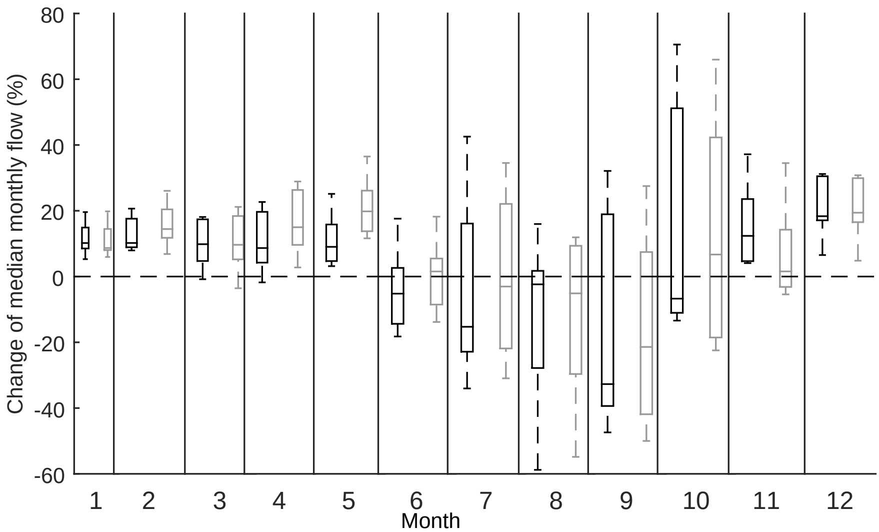


Figure 7.4: Changes of median monthly total flow in 2050 for the Plankbeek catchment under traditional management (black) and adapted management (grey) with reference to historical conditions (1985-2014). A positive change value represents an increase, while a negative value represents a decrease of total flow as compared to historical conditions. Boxplots present the variation of the median monthly flow change between seven GCMs.

Catchment soil water balance and vegetation response

The observed changes to catchment water availability and various subflows originated from changes to the simulated soil water balance, presented in Table 7.6. The increase in total flow under future climatic conditions is due to an increase of total rainfall combined with a small decrease of the rainfall fraction that is lost by evapotranspiration. Furthermore, deep percolation and surface runoff increased under future climatic conditions, both in relative and absolute terms, which led to the increase in overland flow as well as interflow and baseflow. Also from the soil water balance it is clear that adapted management decreased surface runoff as compared to traditional management, while deep percolation increased.

Table 7.6: Simulated components of the catchment soil water balance in 2050 for the Plankbeek catchment under traditional and adapted management as compared to historical conditions (1985-2014). Positive and negative values present an inflow and outflow over the 30 year simulation period. Water storage includes storage of water in the soil and in surface water reservoirs. Values between brackets represent the water flux as a percentage of rainfall. Values for the future are the median flux of the seven GCMs.

Water component	**Historical value (mm)**		**Future value (mm)**			
			Traditional management		**Adapted management**	
Rainfall	25042.4	(100.0)	25801.3	(100.0)	25801.3	(100.0)
Evaporation	-7880.1	(-31.5)	-8541.7	(-33.1)	-8221.8	(-31.9)
Transpiration	-8722.4	(-34.8)	-8091.1	(-31.4)	-8455.8	(-32.8)
Deep percolation	-6129.0	(-24.5)	-6511.7	(-25.2)	-6998.9	(-27.1)
Surface runoff	-2353.2	(-9.4)	-2620.7	(-10.2)	-2130.2	(-8.3)
Net water storage	-66.5	(-0.3)	-66.6	(-0.3)	-66.6	(-0.3)
Total	-108.8	(-0.4)	-105.8	(-0.4)	-107.0	(-0.4)

Since ET_0 increased and evapotranspiration decreased for future conditions (Table 7.4 and 7.6), the vegetation response to climate change caused a 6.6% decrease of the evapotranspiration coefficient when evaluated over the whole 30-year simulation period. $\mathrm{K_{ET}}$ decreased from 0.79 under historical conditions to 0.74 under future conditions for both traditional and adapted management. Figure 7.5 shows that these $\mathrm{K_{ET}}$ changes were even more pronounced during summer months with median decreases of between 5 to 10%. For the GFDL-CM3 climate model there was even an increase of about 30% for August. During fall and winter months, when crop transpiration is limited, the vegetation response to climate change was negligible ($\mathrm{K_{ET}}$ decreased by maximum 1%). Despite the fact that adapted management did not affect $\mathrm{K_{ET}}$ when evaluated over the whole simulation period, it clearly affected monthly $\mathrm{K_{ET}}$ values. Adapted management partly countered the $\mathrm{K_{ET}}$ decrease due to climate change for most months, except for April, May and July.

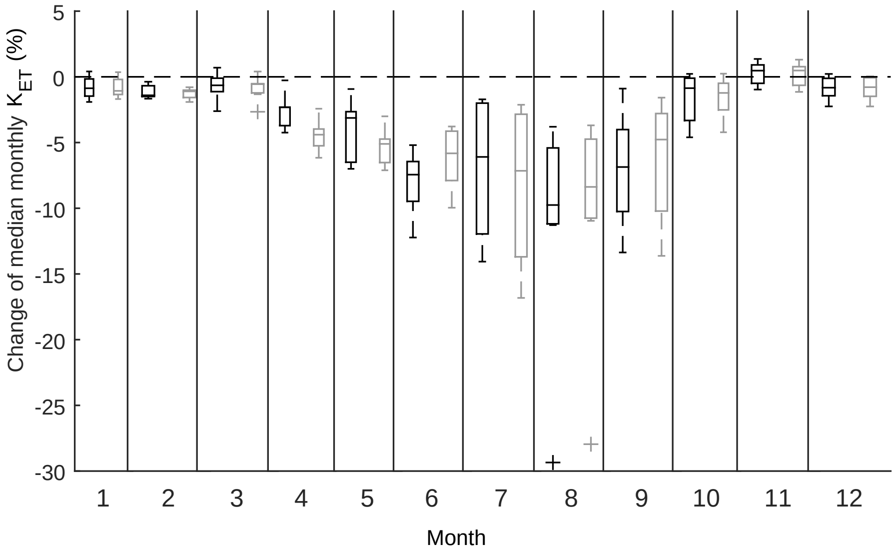


Figure 7.5: Changes of the median monthly catchment evapotranspiration coefficient (K_{ET}) in 2050 for the Plankbeek catchment under traditional management (black) and adapted management (grey) with reference to historical conditions (1985-2014). A positive change value represents an increase, while a negative value represents a decrease of K_{ET} as compared to historical conditions. Boxplots present the variation of the median monthly K_{ET} change between seven GCMs.

Crop yield and water productivity

Crop yield and water productivity in future as compared to historical conditions is presented in Figure 7.6 to Figure 7.8. While Figure 7.6 presents only the impact of climate and management changes on median crop yield and crop water productivity, Figure 7.7 and Figure 7.8 incorporate inter-annual variability. The latter is also quantified by means of the productivity ranges (Table 7.7). Furthermore, Figure 7.7 makes it possible to distinguish between the inter-annual variation and variation caused by the different GCMs of the ensemble. Next to these visual representations, Table B.4 and B.5 list the exact median yield and crop water productivity values under historical and future conditions for each crop.

Median crop yield and water productivity were mostly projected to increase in the future, even without management adaptations. It is very clear from Figure 7.6 that both winter wheat and peas benefited most from climatic changes, with a median yield increases of about 22%. In combination with adapted management, this median yield increase went up to 27% and 36% respectively. For maize, the increase of median crop yield was only small (1%)

without adapted management. This could be explained by maize being a C4 crop, which is less responsive to rising [CO_2] as compared to the C3 crops (see f_{sink} Table 7.2). Furthermore, it is clear from Figure 7.6 that WP_{ET} increased more than crop yield. This indicates that next to an increase of crop yield, seasonal evapotranspiration decreased.

Although median productivity increased, the crop productivity response differed between the different ensemble GCMs. While winter wheat and peas yield response was clearly positive for all GCMs, yield response for maize, potato and sugar beet was less clear. Median crop yield was projected to increase, but some GCMs predicted a yield decrease of up to 12% under traditional management and 3% under adapted management. By contrast, the response for WP_{ET} was never negative. In addition to the fact that GCMs did not agree on the direction of the maize, potato and sugar beet yield response, the variation between different GCMs was also larger for these crops than for winter wheat and peas (Figure 7.6 and Figure 7.7).

Apart from the impact on median crop yield and water productivity, climate change and management adaptations affected inter-annual variability, as seen in Table 7.7 and Figure 7.8. It is clear that under future conditions the difference between minimum and maximum productivity increased. Largest range increases were observed for potato yield (up to 27%) and winter wheat WP_{ET} (up to 74%) (Table 7.7). Only the maize yield and WP_{ET} range became smaller.

Furthermore, Figure 7.8 clearly indicates that, with the exception of maize and sugarbeet yield, the impact of climate change on productivity was larger than the impact of management adaptations. Nevertheless, the impact of management on crop productivity should not be neglected. Management adaptations ensured that crops could benefit more from the changed climatic conditions, leading to an additional yield increase. This extra yield benefit to adapted management was largest for maize, sugar beet and peas. Although adapted management gave an additional boost to crop yield, it could not reduce yield variability. Table 7.7 also shows that for most crops the yield range even further increased when adapted management was considered. Adapted management only stabilized peas yield.

Finally, like yield, largest WP_{ET} responses to management were found for maize, sugar beet and peas. For these crops mulches strongly reduced evaporation, leading to an increase of WP_{ET}. By contrast, tied ridges did not affect WP_{ET} of potato much. For winter wheat, management adaptations (only growing cycle length) affected WP_{ET} slightly negative. The yield increase due to extension of the growing cycle did not compensate for the extra crop evapotranspiration during the extended growing cycle causing reduction of WP_{ET}.

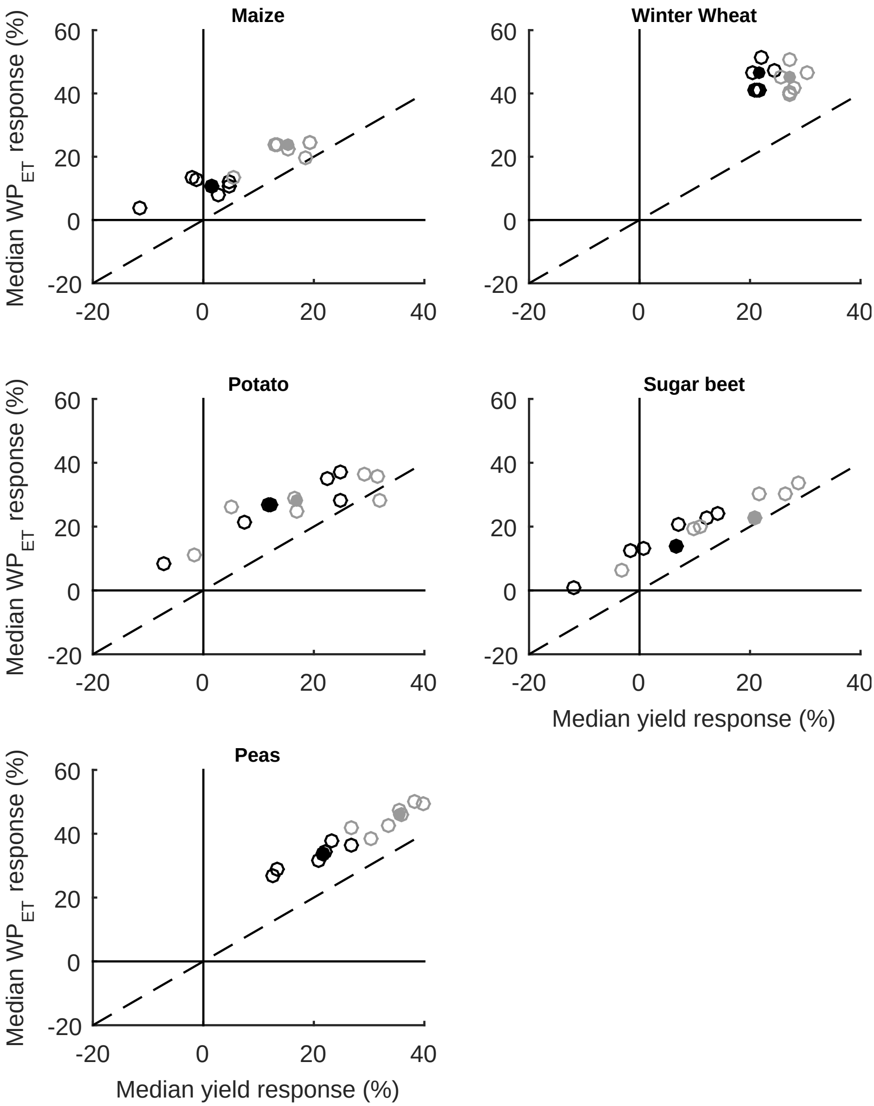


Figure 7.6: Changes to median seasonal crop yield and ET crop water productivity (WP_{ET}) for major crops in the Plankbeek catchment under traditional management (black) and adapted management (grey) in 2050 as compared to historical conditions (1985-2014). A positive change value represents an increase, while a negative value represents a decrease of productivity as compared to historical conditions. Open symbols present the median productivity increase of the seven GCMs, whereas the filled symbol presents the ensemble median.

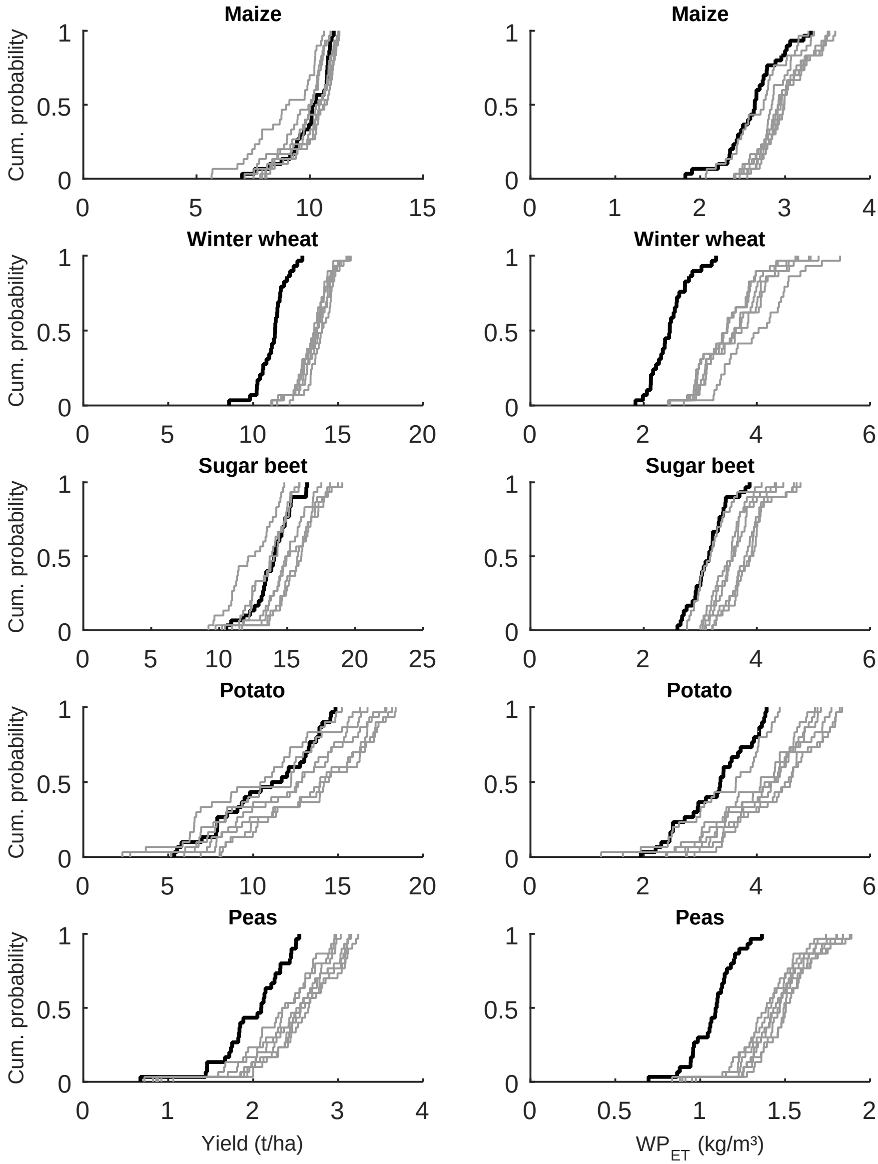


Figure 7.7: Cumulative probability distribution for seasonal crop yield (left) and ET crop water productivity (right) of major crops in the Plankbeek catchment for historical conditions (black) and future conditions with traditional management according to seven GCMs (grey). Probabilities were based on 30 seasonal values for the baseline period 1985-2014 and 30 seasonal values for 2050 for each GCM.

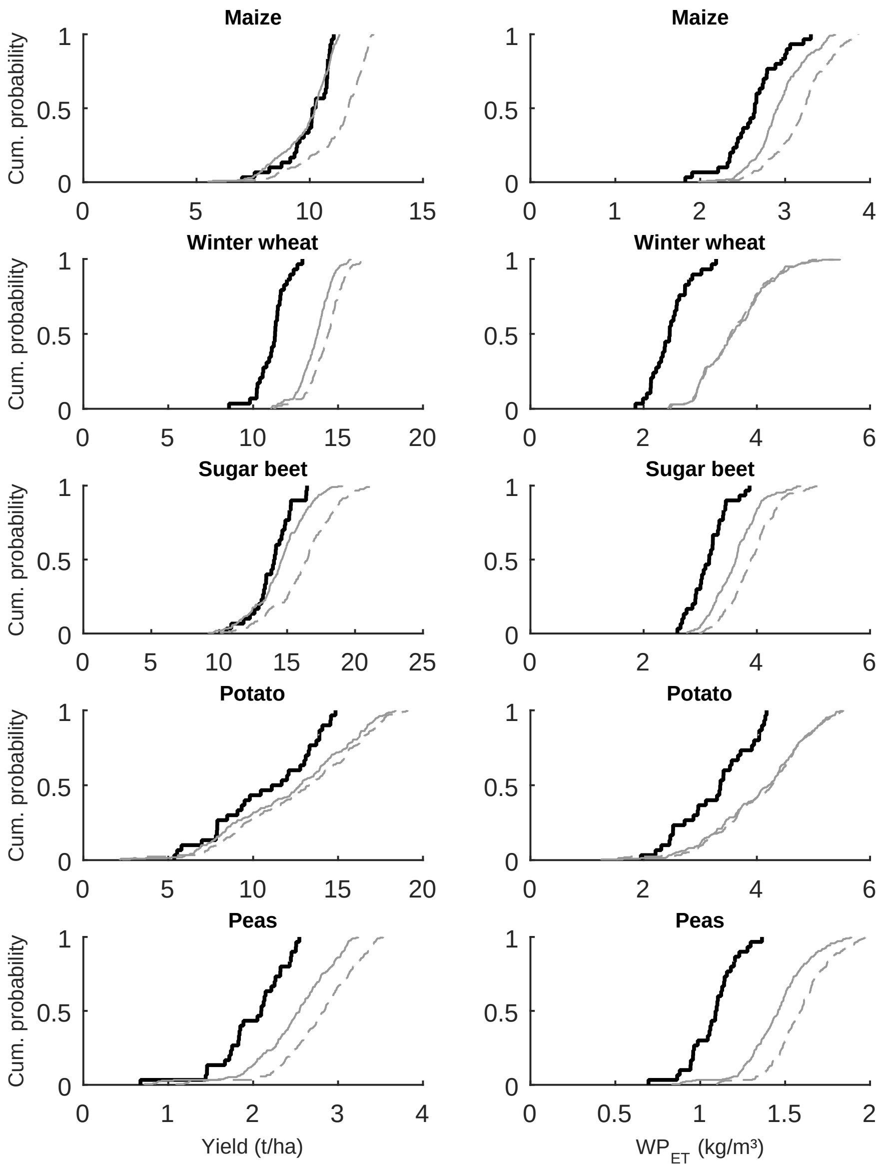


Figure 7.8: Cumulative probability distribution for seasonal crop yield (left) and ET crop water productivity (right) of major crops in the Plankbeek catchment for historical conditions with traditional management (black) and future conditions with traditional (grey full line) or adapted management (grey dotted line). Probabilities were based on 30 seasonal values for the baseline period 1985-2014, and 210 seasonal values for 2050 representing 30 runs for seven GCMs.

Table 7.7: Yield and ET crop water productivity (WP_{ET}) range in 2050 for the Plankbeek catchment under traditional and adapted management as compared to historical conditions (1985-2014). The ranges represent the difference between the maximum and minimum crop yield and WP_{ET} over all simulated seasons (n=30). The range for future conditions is the median range of the seven GCMs. Values between brackets represent the relative change as compared to historical conditions.

	Historical range	**Future range**			
		Traditional management		**Adapted management**	
Yield range (t/ha)					
Maize	4.1	3.4	(-15.6%)	4.3	(+5.9%)
Winter wheat	4.3	4.4	(+2.2%)	4.9	(+13.2%)
Potato	9.5	11.6	(+21.9%)	12	(+26.8%)
Sugar beet	5.9	6.6	(+10.8%)	7.1	(+19.3%)
Peas	1.9	2.3	(+20.5%)	2.2	(+19.0%)
$\boldsymbol{WP_{ET}}$ **range** (kg/m^3)					
Maize	1.5	1.1	(-25.3%)	1.3	(-14.9%)
Winter wheat	1.4	2.5	(+74.1%)	2.4	(+69.8%)
Potato	2.2	2.7	(+21.6%)	2.6	(+18.5%)
Sugar beet	1.3	1.4	(+8.9%)	1.3	(+3.9%)
Peas	0.7	0.9	(+37.3%)	0.8	(+19.8%)

Length of the growing period

Due to changes of weather conditions and resulting available soil water, the length of the growing period (LGP) changed under future climatic conditions. Figure 7.9 presents the impact of climate and management changes on median LGP.

Under future climatic conditions the growing period shortened by 5.5 to 25 days. Largest differences were simulated for sugar beet, closely followed by maize and winter wheat (Figure 7.9). This is logical, as those crops also had the longest LGP under historical conditions, and consequently the largest window for LGP reduction. Furthermore, the extension of the growing cycle length and advance of sowing dates under adapted management (Table 7.3) partly compensated for the LGP decrease in the future.

As LGP is influenced by both temperature and water stress, it is difficult to distinguish which of these factors caused the simulated changes of median LGP that are presented in Figure 7.9. However, the GCMs predicting the largest changes to LGP under future conditions relative to the historical situation

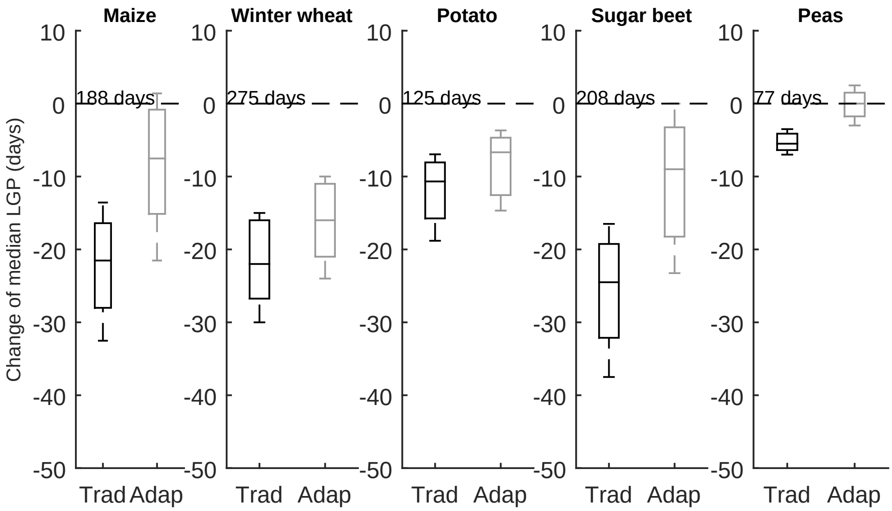


Figure 7.9: Change to the median length of the growing period (LGP) of major crops in the Plankbeek catchment under traditional management (black) and adapted management (grey) in 2050 with reference to historical conditions (1985-2014). A positive change value represents an increase, while a negative value represents a decrease of LGP as compared to historical conditions. The historical median LGP is indicated next to the dashed line representing no change. Boxplots present the variation of the median LGP change between seven GCMs.

(i.e. GFDL-CM3 for spring crops, IPSL-CM5A-LR for winter crops) also corresponded to those predicting the highest temperature increase during the growing season. Hence, it can be assumed that the observed decrease of LGP was mainly caused by increasing temperatures rather than early senescence due to increased water stress.

Water and temperature stress

Since neither fertility stress nor salinity stress were considered in the simulations, the simulated changes to crop productivity and LGP discussed above can be largely attributed to changes of [CO_2] as well as water and temperature stress (Figure 7.10 and Figure 7.11) under future climatic and agronomic conditions.

Under historical conditions, water stress decreased crop production most for potato (median WSI 17%), followed by peas (median WSI 15%), maize (median WSI 4%) and sugar beet (median WSI 3%). By contrast, biomass reduction due to water stress was negligible for winter crops such as winter wheat. Median biomass reduction due to water stress increased due to climate change for potato and sugar beet, as shown in Figure 7.10. For maize and peas the

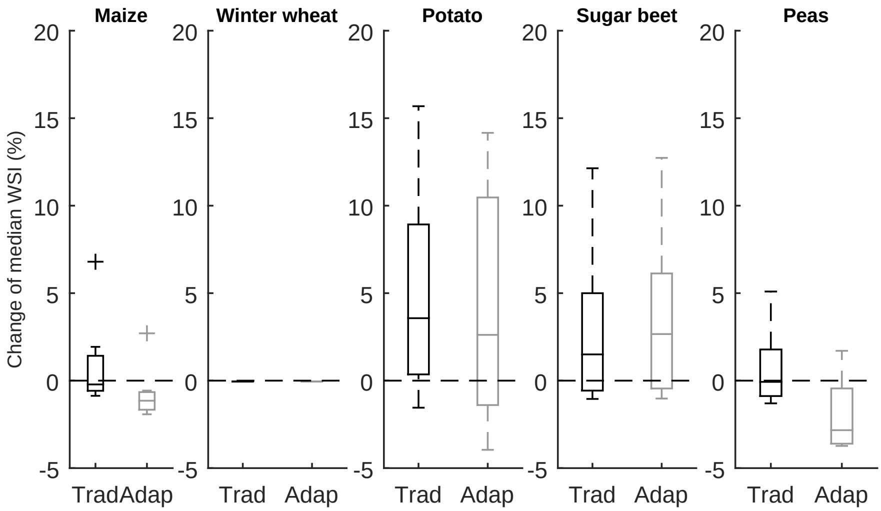


Figure 7.10: Changes to median seasonal water stress index (WSI) for major crops in the Plankbeek catchment under traditional management (black) and adapted management (grey) in 2050 with reference to historical conditions (1985-2014). A positive change value represents an increase, while a negative value represents a decrease of the stress index as compared to historical conditions. Boxplots present the variation of the median stress index change between seven GCMs.

median effect was negligible, but some GCMs predicted an increase of water stress. Furthermore, Figure 7.10 shows that adapted management could partly counteract the increase of water stress, and for maize and peas even improve the situation as compared to historical conditions. By contrast, sugar beet suffered from more water stress under adapted management. Clearly, mulches could not compensate for the increase of water stress at the end of the season due to longer growing cycles. The effect of water stress on winter wheat production remained negligible in the future, regardless of the management strategy.

In addition to water stress, historical crop biomass production was affected by temperature stress. The seasonal heat stress index (HSI) showed that heat stress affecting pollination did not occur under historical conditions and neither under future climatic conditions. The threshold for heat stress (polmx in Table 7.2) for summer crops, being 40 °C, was only reached on one summer day in 30 years, while the threshold for winter crops (35 °C) was only exceeded outside the flowering period of these crops.

The cold stress index (CSI) in Figure 7.11 shows that cold stress was highest for winter wheat (median CSI 33%). Amongst spring crops, maize (median CSI 31%) production was most affected by cold stress followed by peas (median CSI 14%)

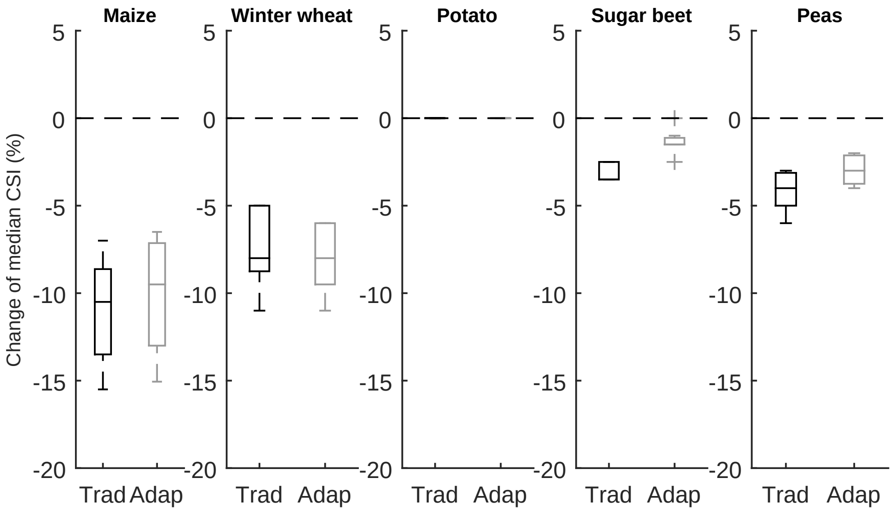


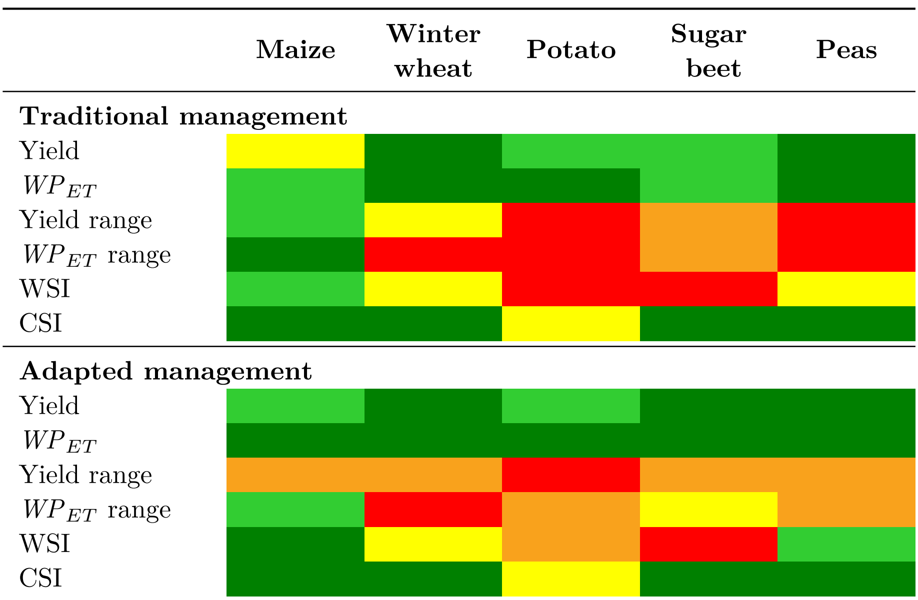
Figure 7.11: Changes to median seasonal cold stress index (CSI) for major crops in the Plankbeek catchment under traditional management (black) and adapted management (grey) in 2050 with reference to historical conditions (1985-2014). A positive change value represents an increase, while a negative value represents a decrease of the stress index as compared to historical conditions. Boxplots present the variation of the median stress index change between seven GCMs.

and sugar beet (median CSI 7%). Clearly, highest cold stress was experienced by crops that are either very sensitive to cold (e.g. high tb and stbio of maize in Table 7.2) or have their growing period during colder periods (winter wheat). Potato production was not affected by cold stress under historical conditions, nor under future climatic conditions. For other crops, cold stress decreased due to rising temperatures in the future climate. Largest decreases of cold stress were noticed for winter wheat and maize, with a median CSI decrease of -8% and -10.5% respectively. Hence, largest benefits to the increased temperature were experienced by crops that suffered most from cold temperatures under historical climatic conditions. Finally, due to the changed growing periods under adapted management CSI increased a little bit as compared to traditional management, except for winter wheat for which CSI remained about the same.

Summary of crop responses to climate and management changes

Generally, crops in the Plankbeek catchment responded positively to climatic changes, with simulated median crop yield increasing up to about 22% and median water productivity increases of up to 46%. With adapted management, yield increased even up to 36%. Despite this overall positive picture, the above presented results clearly illustrate how each crop responds differently to climatic changes and related management adaptations.Table B.4 and B.5 list the exact median values for crop yield, crop water productivity, LGP and stress indices under historical and future conditions for each crop. Table 7.8 presents a categorical summary of the positive and negative impact on median crop productivity variables and stresses as simulated by AquaCrop-Hydro.

Table 7.8: Impact of climatic change and management adaptations on simulated median crop yield, ET crop water productivity (WP_{ET}), yield range, ET crop water productivity range, length of the growing period (LGP), water stress index (WSI) and cold stress index (CSI). Color codes mark the impact strength. Dark green is a strong positive impact (median change by more than 20%), green is a moderate positive impact (median change between 5 and 20%), yellow is a small or negligible impact (median change of maximum 5%), orange is a moderate negative impact (median change between 5 and 20%) and red is a strong negative impact (median change by more than 20%). Impacts are considered positive when yield or WP_{ET} increase, yield or WP_{ET} ranges decrease, and stress indices decrease.



Under historical conditions, maize biomass production loss due to water stress was limited, while cold stress was rather strong. Water stress mildly decreased and cold stress strongly decreased in future climatic conditions, while heat stress remained absent. The combination of lower stress but a shorter growing period resulted in a negligible difference of median yield. By contrast, WP_{ET} increased and productivity became more stable. Introducing adapted management had a positive effect on water stress and further increased productivity.

Winter wheat suffered negligible production losses due to water stress or heat stress under both historical and future climatic conditions. By contrast, cold stress during cold winter months affected winter wheat production a lot under historical conditions. Under future climatic conditions, cold stress seriously reduced so that winter wheat yield and WP_{ET} strongly increased. However, productivity became also less stable, especially for WP_{ET}. Due to extension of the crop cycle, the yield increase was stronger under adapted management. By contrast, adapted management hardly affected WP_{ET} as no water saving practices were implemented.

Potato already suffered from late-season water stress in historical climatic conditions, leading to early senescence and considerable production losses. In addition, this water stress contributed to the high inter-annual productivity variability. Despite the fact that drought stress remained a problem under future climatic conditions, median crop yield increased. It appears that yield increased especially in years with limited water stress, but not in drier years. This led to increased yield variability in future climatic conditions. Implementation of adapted management reduced water stress, and further increased median potato productivity. Neither cold stress nor heat stress affected potato production.

Under historical conditions sugar beet experienced some water stress, especially at the end of the growing cycle. Although water stress increased under future conditions, crop yield and WP_{ET} still increased considerably, especially with adapted management. Unfortunately, also productivity variability increased. Cold stress, which was already rather limited under historical conditions, further reduced under future climatic conditions, while heat stress never affected pollination.

Pea production was already affected by water stress during the canopy expansion phase under historical climatic conditions. In addition, peas also suffered from cold stress due to their rather early sowing date. Under future climatic conditions, water stress did not change much but production was less affected by cold stress. Consequently, yield and water productivity increased very strongly. Under adapted management, water stress could be reduced and productivity increased even more. Unfortunately, also inter-annual variability increased under future conditions, leading to less stable production. Heat stress was absent, as pollination is not considered for legumes such as peas.

7.3.2 Climate change impact under synthesized impact scenarios

Weather conditions

Figure 7.1 displays the median monthly weather conditions for the four synthesized climate scenarios as compared to future weather conditions projected by the ensemble of seven GCMs and historical climatic conditions.

Climate projections for the four scenarios mostly differed during summer and winter months. The high winter scenario (Hw) predicts wetter winters and drier summers, while the high summer scenario (Hs) predicts the opposite. Thereby, drier conditions (low AI) are a combination of a decrease in rainfall and (strong) increase of ET_0, while wetter conditions (high AI) are caused by an increase of rainfall with only a small increase of ET_0. The low scenario (L) is a combination of the two high impact scenarios, as it predicts both winter and summer to be drier. However, the summer is less dry for L as compared to Hw, and winter less dry than for Hs, because ET_0 increases were less strong. The mean scenario (M) projections lie in between the high and low scenarios. In fall (September to November) and spring (March to May), all scenarios predicted the same rainfall increase. Also ET_0 projections differed not much, except for L which projected a slightly lower ET_0 increase in spring and fall months. As a result, spring and fall were wetter for L than for the other scenarios, despite it being the scenario that predicted drier summers and winters. Finally, temperature increases were highest for Hw, and lowest for L for all months. M temperature increases lay in between Hw and L for summer and winter months, but were equal to Hw in spring and fall. Hs resulted in low temperature increases like L, except for winter and spring where temperature increases were equal to M.

Furthermore, Figure 7.1 shows that the synthesized scenarios predicted similar changes to median monthly weather conditions than the ensemble of GCMs. However, as these synthesized scenarios are based on more GCMs than the seven selected for ensemble (Figure B.1-B.3), there were some deviations, especially for rainfall and ET_0. It is clear that both winter and summer rainfall fell outside the ensemble range. Moreover, summer ET_0 projections for Hs were slightly higher than the highest projections of the ensemble.

Water availability

Figure 7.12 displays the impact of future weather changes on total flow at the outlet of the Plankbeek catchment, according to simulations with the four synthesized climate scenarios as compared to flow simulated by the ensemble of seven GCMs or historical time series.

The simulated changes to total flow at the catchment outlet were completely in line with the simulated weather changes. Hs predicted an increase of total flow in summer, but decrease of flow during winter. For Hw, the opposite was true. Despite their different seasonal effect, annual total flow increased for both high impact scenarios. The annual increase was stronger for Hs than for Hw. L predicted decreasing flow both during summer and winter, so that also annual flow decreased. Finally, M predicted a small increase of both winter and summer flow, as well annual total flow.

Furthermore, Figure 7.12 illustrates that flow projections by the four synthesized scenarios covered a wider range as compared to the ensemble simulations. While the ensemble always projected an increase of annual total flow and winter total flow, L projected a decrease of those flows. Moreover, the increase of summer total flow for Hs was much stronger than any of the GCMs projections. These deviations between the ensemble and scenarios were clearly related to the deviations of summer and winter rainfall discussed above.

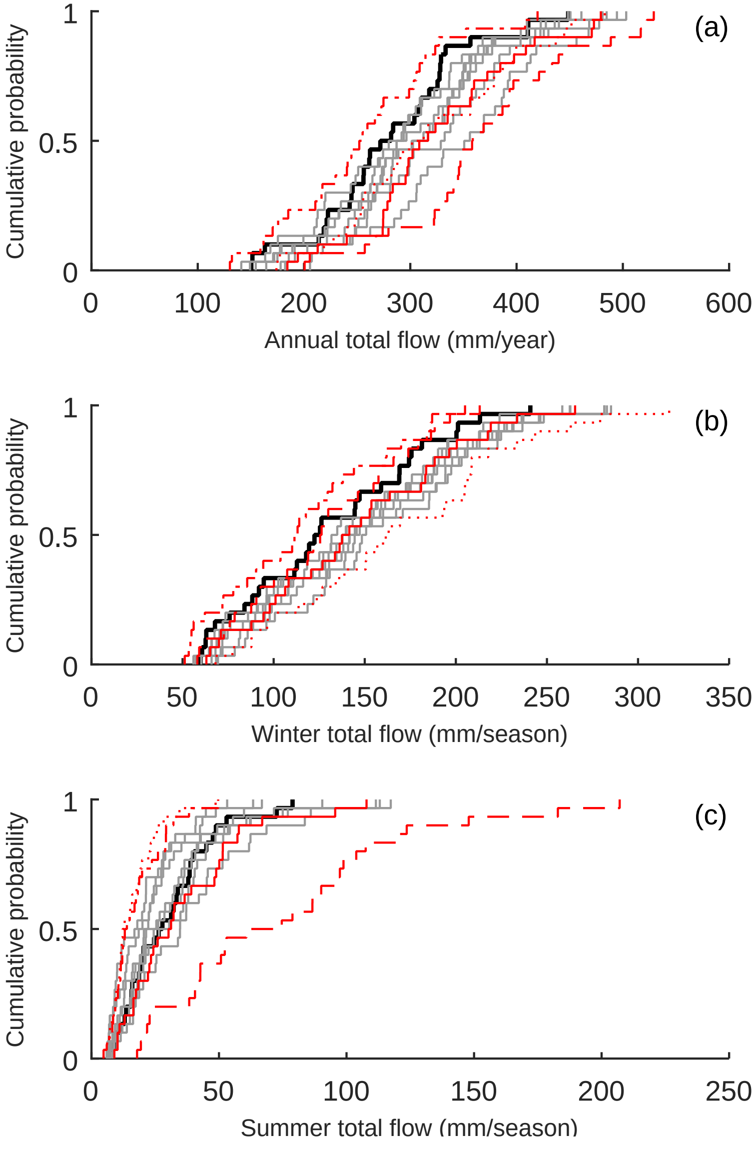


Figure 7.12: Cumulative probability distribution for (a) annual (b) winter and (c) summer total flow for historical conditions (black) and future conditions according to the ensemble of climate models (grey) or synthesized scenarios (red): high summer impact (Hs, dashed red line), high winter impact (Hw, dotted red line), mean impact (M, full red line) and low impact (L, dash-dot red line). Probabilities were based on 30 seasonal values.

Crop yield

Figure 7.13 displays the impact of future weather changes on crop yield in the Plankbeek catchment, according to simulations with the four synthesized hydrological impact scenarios as compared to yield simulated by the ensemble of seven GCMs or historical time series.

The range of yield impact as simulated by the synthesized scenarios did not match the range of the ensemble simulations. Especially for potato and sugar beet the impact range of the synthesized scenarios was much wider than the ensemble range, while for winter wheat and peas the opposite was true. Only the maize range was about the same. Since also summer rainfall predicted by Hs and Hw fell out of the ensemble range, it is not surprising that also yield changes for crops grown in summer predicted by Hs and Hw exceeded the ensemble range.

Furthermore, it is clear from Figure 7.13 that the impact predicted by the synthesized scenarios was not consistent amongst crops. Hs corresponded to the highest yield increase for potato, sugar beet and maize, while L resulted in even higher yield increases for peas. For all spring crops Hw resulted in the largest yield decrease or smallest yield increase. For winter crops, such as winter wheat the opposite is true as Hw caused the largest yield increase. As the dry summers predicted by L were less dry than the dry summers of Hw, L had less negative impact on spring crops than Hw. Moreover, M predictions were only close to the ensemble median for maize and potato. For winter wheat and peas M predicted higher yield increases than the ensemble median, while M gave lower sugar beet yield increases than the ensemble median.

The simulated crop yield impact varied between different crops due to their different sensitivity to temperature and water stress (Table 7.2), but also because of differences in their timing and length of the growing period (Table 7.3). Because of these differences of the growing period, a single scenario might be experienced as a completely different scenario by each crop. For example, while a winter crop mostly faced wetter winter conditions under Hw, a spring crop was confronted with the drier summer conditions projected by Hw. As a result, large impact differences occurred between winter and spring crops. But, even smaller differences in the growing periods amongst spring crops resulted in different responses to the scenarios.

Potato and maize (high to low impact : Hs-M-L-Hw), reacted different to the scenarios as compared to peas (high to low impact: L-Hs-M-Hw) and sugar beet (high to low impact : Hs–L-M-Hw). These differences could be linked to earlier planting date (Table 7.3) of sugar beet (15 April) and peas (1 April) as compared to potato and maize (25 April). With earlier sowing, L resulted in a higher yield impact, because it allowed crops to benefit more from the more

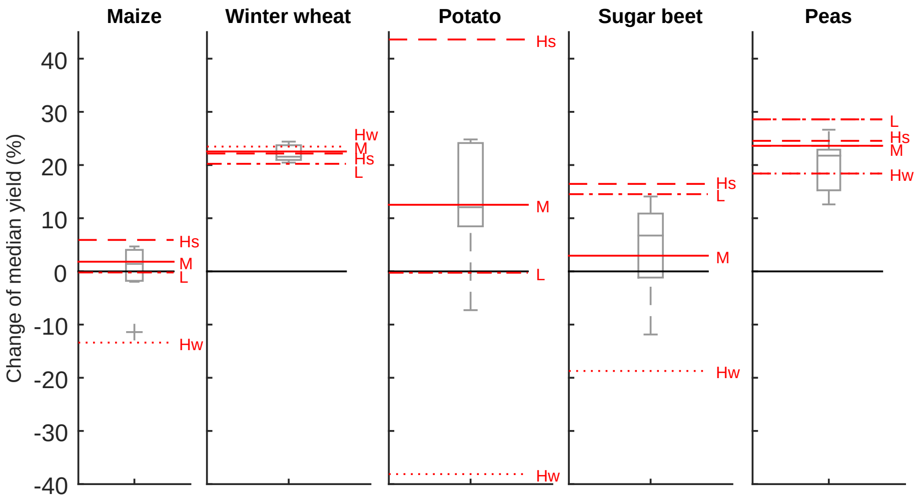


Figure 7.13: Changes to median seasonal crop yield of major crops under traditional management in the Plankbeek catchment in 2050 when simulated by the ensemble of GCMs (boxplots) or synthesized impact scenarios (red lines) with reference to historical conditions (1985-2014). Synthesized scenarios correspond to high summer impact (Hs, dashed red line), high winter impact (Hw, dotted red line), mean impact (M, full red line) and low impact (L, dash-dot red line). A positive change value represents an increase, while a negative value represents a decrease of yield as compared to historical conditions. Boxplots present the variation of the median yield change between seven GCMs of the ensemble.

humid spring conditions predicted by L as compared to other scenarios. This was especially important for peas, which already suffered from water stress in the beginning of the growing season under historical conditions.

Not only the start but also the length of the growing period seemed to affect the crop yield response to various scenarios. Excluding L, all studied spring crops presented the same order of impact: Hs-M-Hw. This order of decreasing yield impact corresponded to the order of decreasing LGP. Spring crops had a longer LGP under Hs as compared to M and Hw, due to lower temperatures and lower probability of early senescence in the more humid summer of Hs. Since crops can accumulate more biomass and yield with longer growing cycles, it is quite logical that yield and LGP impact were linked.

The LGP – yield response relation worked in the opposite direction for winter wheat. Highest temperature increases under Hw resulted in a short growing cycle, but the highest yield increase. For winter wheat, decrease of cold stress during winter was a stronger determinant for the yield response than the length of the period for building up biomass.

7.4 Discussion

7.4.1 Impact analysis

AquaCrop-Hydro shows to be a good tool to simulate the impact of climate change and related management changes for agricultural catchments. This is not surprising as both submodels of AquaCrop-Hydro, i.e. AquaCrop and VHM lumped conceptual models, were already successfully applied to simulate the impact of climate change on crop production (Vanuytrecht et al., 2016, 2014c) and catchment hydrology (Van Steenbergen and Willems, 2012; Vansteenkiste et al., 2012) in Flanders. In addition, it has been shown multiple times that AquaCrop can be used to assess the effect of agricultural management on crop production and the soil water balance (Chapter 2 to 5).

Obviously, the simulated impact of climate and management changes could not be directly validated with field observations of crop production or discharge in the future. However, the simulated impact matched well with other simulation studies. The simulated changes to catchment water availability are in line with the general projections for late 21st century Belgium by Tabari et al. (2015b). Based on rainfall and reference evapotranspiration projections by an ensemble of CMIP5 climate models, also Tabari et al. (2015b) predicted water availability to decrease in summer but increase in winter. Moreover, the impact on crop yield as simulated by AquaCrop-Hydro is similar to the climate change impact simulated under an ensemble of CMIP3 climate models by Vanuytrecht et al. (2016) for maize, winter wheat, potato and sugar beet cultivated in Flanders on a silt loam soil. Vanuytrecht et al. (2016) report a boost to winter wheat, potato and sugar beet yields under future climatic conditions, while maize yield increases are only small. Also management adaptations further boost crop yield for spring crops in the research by Vanuytrecht et al. (2016), although they report a negligible effect of management on winter wheat production. It should be noted that Vanuytrecht et al. (2016) also used the AquaCrop model for their simulation study (except for winter wheat), so that a good match between results is not surprising.

By contrast, comparison of the simulated agronomic impact with historical observations of crop yield responses to climatic changes in Europe revealed some inconsistencies. For example, heat stress nor water stress affected winter wheat production in the simulations for the Plankbeek catchment, while Gouache et al. (2015) report that elevated temperatures or excess rainfall during grain filling as well as winter water logging are important variables that explain historical variation of winter wheat yields in 22 French departments. Also Peltonen-Sainio et al. (2010) report harmful effects of elevated temperatures for cereal yield (barley, wheat and maize), based on analysis of the relations between meteorological conditions and crop yield in various European countries including Belgium. Although differences in environmental conditions between these studies and the Plankbeek catchment might partly explain this mismatch between observed and simulated crop responses to climatic changes, also limitations of the AquaCrop-Hydro model seem to be a source of error.

7.4.2 Limitations

The simulated impact of climate and management changes was inevitably affected by the design of the impact analysis, the approach to generate future weather data, and AquaCrop-Hydro's model structure and its limitations.

Impact analysis design

Because this study only intended to demonstrate application of AquaCrop-Hydro for climate and management impact analysis, certain choices were made to limit the scenario analysis.

First, this study investigated the expected impact for the year 2050 under RCP 8.5. As this scenario projects the highest increase of green house gas emissions, the impact of climate change presented by this study should be seen as a 'worst case' scenario for the near future. Clearly, other target years and RCP scenarios would project completely different climate change impacts.

Next, this study considered only one set of potential management adaptations. Although the selected management practices are realistic, more and different adaptations might be implemented in the future. For example, switching crop type, which is also an obvious climate change adaptation strategy, was not considered. Furthermore, it is also expected that farmers will adjust soil fertility management, weed management and crop protection practices in response to altered nutrient cycles and increased incidence of pest and diseases under future climatic conditions (Olesen et al., 2011). Currently, soil fertility management and weed management can be simulated with AquaCrop-Hydro (Chapter 3 and Chapter 4), but not the occurrence of pest and diseases. Clearly, the simulated impact of agricultural management in this study should merely be seen as an illustration of the potential effect that management could have, rather than as the real management impact that can be expected in the future.

Finally, this study assessed a limited number of evaluated crops and impact indicators. However, since the selected crops represented 70% of the total agricultural area and included both winter and spring crops, the results are expected to be representative for the whole catchment. Additional analysis of the climate change impact on grassland would have been interesting, as it covers 18% of the agricultural area and is an effective erosion control measure. However, the grassland crop parameters could not be validated in Chapter 6 due to lack of data. Consequently, it would be treacherous to focus on the response of grassland to climate and management changes as determined by those parameters.

Approach to generate future weather data

The most crucial limitation of the impact analysis was the approach that was used to generate future weather data.

The ensemble approach was affected by the selection of the ensemble composition. Due to limited availability of GCM perturbation signals for minimum and maximum temperature in the perturbation tool, the ensemble existed of only seven GCMs. A larger ensemble is desired and would increase reliability of the simulated impact range. Moreover, the GCMs of the ensemble originated from only four different research institutes. Since GCMs of the same institute are merely a different parametrization of the same model, it would be better to increase not only the number of GCMs but also diversity of GCMs with respect to their originating institute. Despite the small size and diversity of the selected ensemble, the climatic changes projected by this ensemble match the general trend of changes that was projected by Tabari et al. (2015a,b) for Belgium using a much larger ensemble of CMIP5 climate models.

In addition, sensitivity of model results to the ensemble composition was further investigated by comparison with the climate change impact as simulated using synthesized scenarios. This comparison showed that the synthesized scenarios did not simulate the same impact range as the ensemble of GCMs. The weather, discharge and yield impact range covered by the four scenarios was often larger as compared to the ensemble impact range. This is due to the different number of climate models that was used to obtain perturbation factors for the ensemble and synthesized scenarios. The difference was particularly large for rainfall, with 48 GCMs underlying the synthesized scenarios versus only seven GCMs included in the ensemble. Because of the difference in projected rainfall for the future, also the range of simulated discharge and yield impact deviated between the ensemble and synthesized scenarios.

Although also the synthesized scenarios would be more accurate if based on a wider range of climate signals, especially for T_{min} and T_{max}, it is clear that they present a more realistic view on the uncertainty of future climate projections as compared to the limited ensemble. Moreover, they have the advantage that the impact of climate change can be analysed with only few model simulations. This strongly reduces time requirements for data preparation and model simulation. In addition, clearly defined scenarios can facilitate interpretation of the simulated impacts, and thereby improve uptake of information on climate change implications (Wilby et al., 2009).

Despite these advantages, the use of these synthesized scenarios also has its limitations for agro-hydrological impact assessment as demonstrated by this study. Certainly when the scenarios are defined based on their expected hydrological impact and not agronomic impact as done in this study. On the one hand, the use of hydrologically defined synthesized scenarios worked well to study the impact on river flow at the catchment outlet. The predicted impacts were in line with the expectations under each of the scenarios. Hence, the concern posed by Ntegeka et al. (2014) that scenarios defined according to their expected hydrological impact for a particular catchment in Belgium might not be transferable to other catchments with different locations and properties, was no issue for the Plankbeek catchment. On the other hand, the scenarios did not have a consistent impact on crop production. The synthesized scenarios resulted in different impacts depending on the crop type and timing of the growing period.

Clearly, this study points out the need to define new synthesized scenarios based on their agronomic impact, either yield or water productivity impact. Defining these synthesized scenarios according to the procedure developed by Ntegeka et al. (2014), requires many simulations with an agronomic impact model. AquaCrop is a well suited model for this purpose, as it has small calculation times and input requirements. By using AquaCrop-Hydro, one could even consider developing scenarios based on their combined agro-hydrological impact.

Unfortunately, defining generally applicable agronomic impact scenarios seems extremely difficult. First of all, the impact scenarios would differ for each crop type that has a different growing cycle and sensitivity to climatic changes. This study suggests that for the Belgian conditions a separate set of scenarios for winter and spring crops is the absolute minimum. The results for the Plankbeek catchment indicate that scenarios for winter crops need to be based on the expected temperature changes during the growing season, rather than changes in water availability. A high impact scenario could have a strong increase in temperature, resulting in a strong decrease of cold stress and strong yield increase. Also scenarios for spring crops need to be based on the expected temperature changes during the growing season. But, also changes to water availability should be considered. A high impact scenario for spring crops could represent a small increase in temperature that reduces cold stress while at the same time ensures a long enough growing period, so that final yield increases are strong. In addition, the high impact scenario would need to represent conditions in which crops do not suffer water stress during sensitive periods. As sensitivity to both temperature and water stress is crop (or even cultivar) dependent, scenarios would need to be split up in different categories of spring crops. Second, also other environmental factors complicate development of general agronomic impact scenarios. In particular, soil characteristics and the depth of the groundwater table are highly variable but define water availability to the crop. Hence, scenarios developed based on impact simulations for one soil type are likely not transferable to fields with different soil types.

Hence, the challenge to define agronomic impact scenarios would be to group cropping systems in such a way that a limited set of scenarios can simulate a consistent impact for all crop and soil types. Only when one succeeds in defining a limited number of agronomic impact scenarios, one could consider development of agro-hydrological impact scenarios. Thereby one needs to deal with the additional complication that various crop combinations are cultivated within the same catchment.

Model limitations

AquaCrop-Hydro has some limitations to study the impact of climate change and related management adaptations, which stem from limitations of its two submodels.

First, AquaCrop applies highly simplified procedures to simulate the effect of agricultural management such as mulches and tied ridges (Section 2.6). Consequently, some of their potential effects on crop production or the soil water balance are not considered. While mulches reduce soil evaporation, their effect on soil temperature, soil nutrient status, crop germination and crop development is not directly considered during AquaCrop simulation. In addition, the breakdown of organic mulch material during the growing season is not taken into account. Also the effect of tied-ridges on soil erosion and soil fertility is not considered, because AquaCrop only simulates their inhibition of surface runoff.

Moreover, AquaCrop considers the effect of heat stress only on pollination or indirectly through increased ET_0 (Subsection 2.5.2). No direct effect of heat stress on flowering and grain filling is considered in the AquaCrop simulation procedure. This leads to the unrealistic absence of heat stress for winter wheat and maize simulations. Introducing an adjustment of the harvest index to heat stress, as proposed by Villalobos et al. (2015), seems indispensable to improve model simulations, especially for future climatic conditions where temperatures are higher. Moreover, due to absence of processes such as cold acclimation, vernalization and dormancy in the AquaCrop simulation procedure, crop response to cold temperatures is simulated less accurately for winter crops. Vanuytrecht (2013) already pointed out that acceptable simulations of winter wheat production under historical conditions could be obtained by adjustment of conservative crop parameters, but that this leads to unrealistic and too strong responses of winter wheat development and production to future temperature increases. In addition, this leads to the wrong impression that winter wheat suffers from cold stress, while this simulated cold stress is merely a technical solution to slow down crop development and biomass production during winter rather than a real stress experienced by the crop. Currently, options to optimize AquaCrop simulation procedures for winter crops are being investigated (Vanuytrecht et al., 2014a). However, as long as model procedures are not updated, AquaCrop should be replaced by more appropriate models, such as the Sirius wheat model (Jamieson et al., 1998), when winter crops are the main interest of the impact analysis or cover a large part of the catchment.

In addition, like other crop models AquaCrop has its limitations to simulate crop response to extreme weather conditions such as droughts, heavy precipitation, heat waves, extreme cold, wind and hail storms. However, the incidence of such extreme weather conditions, which seriously impact crop production and water availability, is likely to increase due to climate change (IPCC, 2014). Currently, options to improve model simulation of crop response to extreme weather conditions are being investigated in the framework of the MODEXTREME (MOdelling vegetation responses to EXTREMe Events) project (Villalobos et al., 2015).

Second, also the hydrological submodel has some limitations due to its conceptual nature. Because of lack of observations for the future, it is impossible to calibrate the hydrological parameters to match the future catchment response behaviour. Consequently, for this impact analysis the same set of hydrological model parameters was used for all model simulation. These parameters were calibrated and validated for historical conditions in Chapter 6. When using the same set for future conditions, it is assumed that neither management changes nor vegetation changes in response to climate change would affect catchment hydrological behaviour. However, in reality field management adaptations such as tied ridges and mulches might affect overland flow recession time. Also denser canopy cover, as a result of more favourable climatic conditions for crop growth, could affect water routing. Nevertheless, the use of fixed recession constants is common practice in hydrological climate change impact assessment. Amongst others Taye et al. (2011) and Van Steenbergen and Willems (2012) used fixed model parameters for climate change impact assessment with VHM conceptual models.

7.4.3 Implications

Many lumped conceptual hydrological models could have been used to study the impact of climate change on discharge at the outlet of the Plankbeek catchment. However, AquaCrop-Hydro has the advantage of being more dynamic with respect to the catchment's response behaviour to climatic changes. The soil water balance simulations of conceptual hydrological models under climate change are only affected by changes in input of rainfall and potential evapotranspiration, but not by changes to vegetation in the catchment. The relation between actual and potential evapotranspiration remains unaffected by climate change, except for the soil water balance correction. Consequently, vegetation feedbacks to the hydrological system are completely neglected. By contrast, AquaCrop-Hydro simulates actual evapotranspiration not just based on climatic conditions (ET_0) and the soil water balance, but also based on the simulated crop canopy development. Hence, when climate change causes alterations to the canopy structure, the simulated evapotranspiration will be adjusted accordingly. This research showed that the catchment's evapotranspiration coefficient decreased by up to 10% during summer months for future climatic conditions. Since about 65% of the rainfall in the Plankbeek catchment does not reach the river but is lost by evapotranspiration, conceptual hydrological models make a considerable error when neglecting the vegetation responses to climate change. Especially for accurate simulation of water availability during summer months it is crucial to use a dynamic equation for estimation of evapotranspiration. van Walsum and Supit (2012) already stressed that a static approach like adopted by conceptual hydrological models should be abandoned in favour of a dynamic approach. AquaCrop-Hydro provides an opportunity to do so, without forcing people to switch to complex physically based models with high data and calibration requirements.

Furthermore, this study highlighted the importance of taking into account management changes for climate change impact assessment. Yield increases due to climate change were up to 14% higher with adapted management as compared to traditional management. Although total flow was not affected much by management on a yearly basis, flow during late spring, summer and fall was strongly affected by agricultural management practices. Moreover, also the contributions of different subflows to total river discharge were affected by management. This clearly indicates that it is dangerous to neglect the agricultural management aspect when assessing the impact of climate change for agricultural areas. Nevertheless, an analysis of 221 peer reviewed studies on simulation of crop response to climate change showed that only 75% considered management adaptations, with only 33% varying at least two management practices.

Unfortunately, while climate change projections are widely available, projections for future management are sparse. It is extremely difficult to predict management changes for the future, because management is not just affected by environmental factors but also by factors such as farmers' behaviour, legislation and technology advances. For that reason, published information is sparse, mostly based on extrapolation of historical trends, considers few crops, studies one management practice at the same time, and links changes of this management practice just to one determinant factor. For example, this study relied on changes of the planting date based on projected temperature changes. Thereby, the effect of soil wetness and field accessibility on the planting date was not considered. Moreover, an holistic projection of changes to the combination of planting date, growing cycle length and surface practices was absent. Clearly, also AquaCrop-Hydro remains liable to the lack of projections of future agricultural management. Seeing that management can have such a large impact, development of holistic management scenarios deems indispensable. Moreover, an ensemble of such scenarios should be considered due to the high uncertainty related to farmers management decisions.

In addition to this lack of information, agricultural management is often disregarded in hydrological impact assessments because of model restrictions. On the one hand, conceptual models cannot explicitly take into account management changes due to lack of physically based model equations and parameters. On the other hand, accurate parametrization to consider management practices is often neglected in physically based models, due to restrictions of data or time for data preparation and model simulation. Fortunately, AquaCrop-Hydro facilitates consideration of agricultural management practices in climate change impact assessment, as simulation of management practices requires few input parameters that are easily available.

Besides the benefit of a dynamic simulation of the climate change impact with AquaCrop-Hydro, the impact can be analysed on different scales. AquaCrop-Hydro allows to study the impact of climate change both on agricultural production at field scale as well as catchment water availability. Such a combined analysis is rarely done, but crucial nevertheless. As shown by this study, agricultural management can have a large impact on seasonal water availability in the area, where different actors share the available water resources. Furthermore, also feasibility of climate change adaptations for improving agricultural productivity are often highly dependent on water availability. For example, farmers could benefit more from higher yield due to climate change when the effect of drought stress during summer would be avoided by irrigation. However, shifting from rainfed to irrigated agriculture is only feasible when sufficient irrigation water is available. This study already indicated that supplemental irrigation using river water in the Plankbeek catchment would prove difficult as river flows during summer also decreased due to climate change.

7.5 Conclusion

AquaCrop-Hydro enables simulation of the impact of climate change and related adaptation management strategies on crop production as well as catchment water availability, without large data and calibration requirements. However, further development of AquaCrop is necessary to improve the simulation of crop responses to temperature and extreme events. Because of AquaCrop-Hydro's dynamic nature and the possibility to include the effect of agricultural management, it is expected that its impact projections are more realistic than those of static conceptual hydrological models which cannot take into account management adaptations. Using synthesized climate scenarios can facilitate climate change impact assessment with AquaCrop-Hydro, and avoid biased uncertainty analysis by using a small ensemble of climate models. However, new synthesized climate scenarios that focus on the agronomic impact in addition to the hydrological impact of climate change need to be developed.

Chapter 8

Discussion, conclusion and outlook

It was formulated in the introduction (Chapter 1) that the goal of this research project was to develop and evaluate a parsimonious, widely applicable agro-hydrological model that can be used to evaluate the effect of agricultural management from field to catchment scale. This final chapter evaluates how far the developed AquaCrop-Hydro model meets the targeted criteria, and which aspects require further model development. Also, the findings on the practical use of this new agro-hydrological model are discussed. Finally, application as well as limitations of AquaCrop-Hydro to support sustainable land and water management decisions are discussed.

8.1 Model assessment

Criterion 1: The model simulates crop production and water productivity at field scale, as well as hydrological processes and water availability at catchment scale

Assessment: Being a combination of the AquaCrop crop water productivity model and a VHM conceptual hydrological model, AquaCrop-Hydro fulfils this first criterion to a large extent.

AquaCrop-Hydro is indeed able to simulate crop water productivity as well as hydrological processes and water availability. The AquaCrop submodel deals with simulation of crop development and productivity as well as the soil water balance. The conceptual hydrological model, on the other hand, simulates overland flow, interflow and baseflow that form the river discharge at the catchment outlet. The latter is considered to be an estimate for water availability in the catchment.

Due to the strong conceptual nature of both submodels, not all hydrological processes are described in a detailed physically based manner. The soil water content, and corresponding processes of infiltration, transport, and percolation of water in and out the soil profile are simulated in a physically based way. By contrast, generation of surface runoff is based on the curve number method, which is determined by empirical parameters. Also, overland flow, interflow and baseflow are simulated using empirical linear reservoir functions. Hence, AquaCrop-Hydro describes small scale processes that determine the volume of water in a physically based way, whereas the processes that determine the temporal variation of water flow at a larger scale are dealt with in a conceptual way. Due to this conceptualization, the model provides little information on the nature and functioning of these processes.

Furthermore, the detail with which some hydrological processes are described in AquaCrop-Hydro might not be sufficient. First, it was demonstrated in Chapter 6 that surface runoff generation was not described accurately by AquaCrop-Hydro. Due to the model's daily time step, the impact of sub-daily rainfall intensity on surface runoff generation is neglected. This limits the model's application for flood modelling. However, if rainfall data with smaller time steps (e.g. 15 minutes) are available, surface runoff simulation might be improved by adjusting the model. This requires replacing the daily AquaCrop runoff calculation procedure by a procedure that is more suitable to small time steps (e.g Green and Ampt method). As a consequence, the surface runoff procedure would no longer be part of the AquaCrop submodel, but remain closely linked via the soil water balance.

Second, also the interaction between the unsaturated and saturated zone is not described well in AquaCrop-Hydro. The current model structure, proposed in Chapter 6, simulates that a part of the water percolating out of the soil profile goes to the groundwater table and reaches the river via baseflow. In the opposite direction, it is not the baseflow reservoir that determines the capillary rise, but the user-specified depth of the groundwater table below the soil surface. The latter is a remnant of the AquaCrop soil water balance model, which considers the groundwater as a user-defined boundary condition. The potential discrepancy between the user-specified input of the groundwater table depth on the one hand and simulation of the groundwater volumes on the other hand brings about the fact that a closed water balance can not be assured. In addition, it is practically infeasible to obtain sufficient data to specify the time variable groundwater table depth for each land unit within the catchment, and even impossible for future time horizons.

This issue regarding the unsaturated-saturated zone interaction is no problem when the model is applied to areas where the groundwater table is deep so that the interaction between the unsaturated and saturated zone is one-directional. For example, in Chapter 6 and 7 the proposed model structure was applied for the Plankbeek catchment, where capillary rise from the groundwater was neglected. By contrast, for other areas where a shallow groundwater table significantly affects the soil water balance, the proposed model structure may be less suitable. For those areas it is crucial to consider the unsaturated-saturated zone interaction simultaneously in both directions.

Clearly, AquaCrop-Hydro's procedures for simulating the upward flow from the saturated to the unsaturated zone need to be updated to make the model applicable to groundwater-dominated catchments. First, the simulated volume of capillary rise needs to be subtracted from the baseflow recharge at each time step. Second, instead of a user-specified value, the depth of the groundwater table could be derived from the simulated volume of water in the baseflow reservoir at each time step. To preserve model simplicity, an empirical approach seems most suitable. The generalized conceptual model structure by Willems (2014), which was partly implemented in AquaCrop-Hydro, does not account for the upward flow between the baseflow and soil reservoir. But, inspiration can be found in the NAM conceptual model (DHI, 2009). NAM simulates capillary rise between a groundwater storage reservoir and root zone storage reservoir based on the simulated relative water content of the root zone storage reservoir and depth of the groundwater table, as well as a parameter corresponding to the depth of the groundwater table for a capillary flux of 1 mm/d. It should be noted that by implementing such algorithms to simulate the groundwater table depth, model complexity and data requirements will increase. For that reason, the flexibility to discard this model component when applying AquaCrop-Hydro for catchments without a shallow groundwater table as well as the use of a constant groundwater table depth should remain an option.

Furthermore, AquaCrop-Hydro is able to consider both field and catchment scale processes. Crop development and production are simulated on point-basis, representing one homogeneous field or land unit. River discharge and corresponding subflows are simulated at catchment scale using a lumped approach. The soil water balance is simulated at both scales. Scaling up the soil water balance from field to catchment scale is done as suggested by Wesseling and Feddes (2006) using a semi-distributed approach. Because the catchment is not represented in a fully distributed manner, AquaCrop-Hydro neglects spatial distribution of land units and spatial connectivity which is important for some hydrological processes. Neither the interaction between the soil water balance of various land units, nor the spatial variation of some flow components is considered in AquaCrop-Hydro. For example, surface runoff generated in one field can not be considered as run-on in a neighbouring field. Also, there is no difference between the recession time of surface runoff generated in land units close to the catchment outlet as compared to surface runoff generated in the upstream area.

The lack of a fully distributed description of hydrological processes might affect AquaCrop-Hydro's simulation accuracy. When studying the hydrological impact of urbanization, Poelmans et al. (2010) found that surface runoff calculations are very sensitive to accurate spatial information, especially for small catchments. Nevertheless, AquaCrop-Hydro was developed focussing on an accurate description of the soil-plant-atmosphere system in order to accurately simulate crop response to environmental changes and agricultural management. To preserve the model's parsimonious nature, a more detailed spatial representation of hydrological processes was abandoned.

Switching to a fully distributed approach would not only increase data requirements but is also technically difficult with the current AquaCrop software. Crop models, such as AquaCrop, operate at point-basis because they were initially developed to study crop production in a single homogeneous field. Since large scale scenario analysis of agricultural production is becoming more common, modelling frameworks have been developed or adjusted to deal with spatial heterogeneity. However, most of these frameworks run a series of point-based simulations for different spatial units which do not interact which each other (Holzworth et al., 2015). Examples are the AquaCrop-GIS framework (Lorite et al., 2013) or the GeoSim toolbox (Thorp and Bronson, 2013), which enable AquaCrop simulations for multiple locations using geospatial data within a geographic information system. To date, only APSIM (Holzworth et al., 2014) and CropSyst (Stöckle et al., 2003) allow simultaneous simulation of multiple points that interact with each other. This interactive multiple-point capability allows to simulate, for example, runoff generated on one field contributing water to a neighbouring field as run-on, or tall trees on one field depriving small crops in the neighbouring field from light (Holzworth and Huth, 2004). Similarly, interactive multiple-point functionality would need to be added to the AquaCrop model in order to improve spatial representation of hydrological processes in AquaCrop-Hydro. Especially, linking soil water balance calculations of multiple simulations by incorporating a run-on component in the soil water balance would be crucial.

Criterion 2: The model considers the effect of management and environmental changes on crop transpiration and crop (water) productivity, as well as catchment hydrology

Assessment: Due to the physically based nature of the AquaCrop submodel, AquaCrop-Hydro fulfils this second criterion, although further improvements are possible.

As discussed in Chapter 2 and demonstrated in Chapter 3 to 5, AquaCrop enables simulation of the effect of agricultural management on crop canopy development, crop transpiration, crop biomass production, crop yield, crop water productivity and various components of the soil water balance in a cultivated field.

A wide variety of agricultural management practices can be considered by AquaCrop-Hydro, including crop management, soil management, field surface management, mulches, soil fertility management and weed management practices. Unfortunately, not all of them are implemented in AquaCrop as a management practice, which makes their use intricate. A significant improvement in that matter was made in AquaCrop 5.0 for field surface management practices that affect surface runoff. Whereas in previous AquaCrop versions the curve number was solely a soil parameter, the effect of field surface management on this parameter is now explicitly implemented in the management module. Further improvements could be made by implementing runoff agriculture as a field management practice in AquaCrop. This avoids the parallel simulations that are currently required.

Furthermore, all management practices are implemented in a simplified way to safeguard AquaCrop's parsimonious nature. Therefore, the model can be used for general assessment of the effect of management practices on the soil water balance, crop growth and (water) productivity, but is less suitable for detailed analysis. For example, AquaCrop limits the effect of mulches to reduction of soil evaporation. Hence, the model can not consider their effect on soil structure, soil temperature, soil fertility or crop germination, which might have an additional effect on crop production. Furthermore, it was discussed in Chapter 3 and 4 that because of the simplified procedures for soil fertility and weed management, AquaCrop can not provide information on required fertilizer doses or weed control operations. Moreover, the model can neither be used for detailed analysis of nutrient fluxes, nor for gaining insight in the crop-weed competition mechanisms.

Moreover, with the exception of weeds, neither the effect of pests (including animal pests, pathogens and viruses) nor diseases can be directly simulated with AquaCrop. However, when field observations of the impact of such pests at a certain time in the growing season are available, the simulated canopy cover or biomass can be manually updated to account for potential yield losses in the simulation of the remaining growing season. Because of the complexity and huge variety of processes through which pests affect crop development and production, their consideration through implementation of new algorithms in AquaCrop seems difficult without compromising the model's parsimonious nature.

Next to agricultural management, also the agronomic impact of climate change can be simulated with AquaCrop as discussed in Chapter 2 and demonstrated in Chapter 7. The effect of climate change is considered by adaptation of the weather and [CO_2] input variables. These climate changes affect the simulated crop canopy development, crop transpiration, crop biomass production and crop (water) productivity according to the procedures that describe crop responses to abiotic factors such as water availability, air temperature and CO_2 concentration (Section 2.5).

It should be noted that these procedures show room for improvement. The scenario analysis in Chapter 5 indicated that the simulated crop responses to water stress did not always meet expectations. Also Castañeda-Vera et al. (2015), Ahmadi et al. (2015), and Abedinpour et al. (2012) have mentioned that AquaCrop performs less good under conditions of extreme water stress. Chapter 5 showed that water stress is not always well represented because it is derived from the average soil water content over the whole root zone. This average soil water content does not take into account water and root distribution within the soil profile, which strongly defines the level of water stress experienced by a crop. It is, for example, highly unlikely that a crop would suffer from water stress when the topsoil with high root density is very wet even if the subsoil is dry. Clearly, AquaCrop calculation procedures for water stress should be further improved by calculating water stress based on a weighted average soil water content, using the root distribution as a weighting factor. In addition, expansion of the root zone should only be slowed down by the presence of a restrictive soil layer and not completely stopped as it is currently the case.

Next, also the procedures to simulate crop responses to air temperature can be improved. Chapter 4 as well as Chapter 7 showed that crop development and production of winter wheat was not simulated realistically because AquaCrop does not consider processes such as cold acclimation, vernalization and dormancy. This issue was already mentioned by Vanuytrecht et al. (2014a), but so far no new procedures for winter crops have been implemented. Furthermore, Chapter 7 indicated that the effect of heat stress on crop production is underestimated, especially the impact of extreme temperatures. A correction of the harvest index to high temperatures, as proposed by Villalobos et al. (2015), would be a first step to improve model simulations.

Aside from altered daily weather conditions, climate change will also bring about increased incidences of extreme events such as droughts, heavy precipitation, heat waves, extreme cold, wind and hail storms (IPCC, 2014). To date most crop models, including AquaCrop, can not take such extreme events into account. For that reason, the impact of climate change simulated by AquaCrop-Hydro, as presented in Chapter 7 for the Plankbeek catchment, should be interpreted with care. Future research, such as conducted in the framework of the MODEXTREME (MOdelling vegetation responses to EXTREMe Events) project (Villalobos et al., 2015), is extremely important to improve model structures and tackle this problem.

Although this research focused on climate change, also other environmental changes can be simulated with AquaCrop-Hydro. For example, the effect of soil degradation or changes to the groundwater table can be considered by changing the relevant AquaCrop input parameters. Furthermore, also simulation of land uses changes can be done by adaptation of the relative area of each land unit within the catchment when scaling up the soil water balance from field to catchment scale.

Moreover, since AquaCrop adjusts the simulated canopy cover and soil water balance to agricultural management and environmental changes, also the catchment soil water balance and water availability as simulated by AquaCrop-Hydro account for the effect of agricultural management and environmental changes.

This dynamic approach of AquaCrop-Hydro is crucial for accurate simulation of the catchment soil water balance and water availability. It was quantified for the Plankbeek catchment in Chapter 7 that ignoring management adaptations in response to climate change could lead to underestimation of future water availability during summer months of up to 12%. Likewise, it was quantified that neglecting crop responses to climate change, as often done in conceptual hydrological models, could lead to overestimation of the catchment's evapotranspiration by about 10% during future summer months. Because evapotranspiration is a very large component of the soil water budget, such overestimation could cause considerable errors to the simulated discharge at the catchment outlet. This error could be further quantified by comparing the discharge simulated by the dynamic AquaCrop-Hydro model under future climatic conditions with results obtained by a static conceptual hydrological model. Conceptual models defined according to the VHM approach by Willems (2014) are most appropriate for that purpose given their large similarity with AquaCrop-Hydro.

Despite the dynamic approach of AquaCrop-Hydro, it should be noted that neither agricultural management nor environmental changes directly affect the simulated water routing at catchment scale. Also in Chapter 7, the effect of climate change and related management adaptations was simulated by adjusting only the field scale input variables and parameters. The lumped hydrological model parameters, that define the recession times of the various subflows and the baseflow-interflow proportion in the catchment, were left unchanged.

In reality, one would expect that the catchment response behaviour alters when management or environmental changes affect catchment characteristics. In particular, the overland flow recession time will be affected by changes to the soil surface characteristics. For example, field surface management such as ridges increase surface roughness and consequently slow down overland flow and thus increase the recession time. Also, land use changes or altered crop growth patterns due to climate change modify the soil surface and thus influence overland flow recession times. Furthermore, agricultural management could affect the soil's hydraulic conductivity and consequently the interflow recession time. However, this can already be accounted for by AquaCrop during simulation of drainage out of the soil profile, so that it would not require additional adjustment of the interflow recession constant of AquaCrop-Hydro. In addition, management practices might affect soil characteristics that determine the capacity to transport water via lateral drainage (interflow). For example, interflow might decrease if soil layers inhibiting water percolation are broken up during land preparation. As such, management can also affect the interflow-baseflow proportion. Finally, as opposed to overland flow and interflow, it is unlikely that baseflow recession time would be affected by agricultural management or environmental changes.

It is clear that abandoning the assumption of static catchment response behaviour to agricultural management could increase accuracy of model results, especially for overland flow and interflow. However, the empirical nature of AquaCrop-Hydro's hydrological model parameters make it difficult to adjust them according to the management practices of the individual landunits. Nevertheless, it might be possible to relate conceptual model parameters to observable catchment characteristics. An example was set by Tran et al. (2016) who disaggregated lumped catchment scale conceptual models to higher spatial resolutions based on physical catchment characteristics such as topography, land use and soil type. Such a link between empirical model parameters and observable catchment characteristics could support the adaptation of the conceptual model parameters to agricultural management.

Criterion 3: The model is parsimonious, i.e. accomplishes the desired level of explanatory power with a minimum number of easily obtainable input data and parameters to be calibrated

Assessment: Due to the parsimonious nature of both submodels, AquaCrop-Hydro fulfils this third criterion.

Both submodels require relatively few input or calibration data. AquaCrop's low requirements for easily obtainable input data were discussed in Chapter 2 and demonstrated by simulating crop production for data-scarce experimental sites in Ethiopia, Bolivia and Nepal (Chapter 3 and 4). Also, model comparison studies by Abi Saab et al. (2015), Castañeda-Vera et al. (2015), Todorovic et al. (2009), and Hunink et al. (2011) have confirmed that AquaCrop has lower data requirements than other crop models such as CropSyst, CERES, STICS, and WOFOST. In addition, comparison of AquaCrop and SWAT input requirements in Chapter 6 shows that both models require a similar amount of data to describe the soil-plant-atmosphere system in a single land unit. However, AquaCrop requires parameters that are more easily obtainable. In addition, AquaCrop has a more detailed description of crop response to water stress, which is very important for agro-hydrological models. Next to the AquaCrop input data, only a series of daily river discharge observations is required to calibrate AquaCrop-Hydro's hydrological model parameters. Such time series is commonly available, even in data-scarce regions.

Since AquaCrop-Hydro is partly physically based, the model requires calibration of just a few empirical model parameters using a transparent guided data-based approach. Calibration of AquaCrop crop parameters is only necessary when simulating new crops (not included in Table C.1), or when soil fertility or salinity stress is considered. During calibration, a user should focus on the most sensitive parameters according to the global sensitivity analysis by Vanuytrecht et al. (2014b). Also, identification of good parameter values is facilitated by the transparent stepwise calculation procedure of the AquaCrop model. Furthermore, AquaCrop-Hydro's hydrological model parameters can be calibrated according to the stepwise procedure by Willems (2014) as demonstrated in Chapter 6. This procedure is supported by subflow separation using the WETSPRO tool (Willems, 2009). Also, the baseflow-interflow separation equation can be calibrated from the filtered subflows.

Furthermore, input and calibration requirements of AquaCrop-Hydro are strongly reduced when using the default soil, management or crop parameter values that are provided in the AquaCrop database (Appendix A). Chapter 6 illustrated that good estimates of crop production and water availability in the Plankbeek catchment could be obtained relying on default soil and management paramaters. Data requirements are especially reduced when the study catchment contains crops that are included in the AquaCrop database (Table C.1), because the majority of these pre-calibrated parameters does not need any alteration. Only the non-conservative parameters need to be fine-tuned to the local cropping system. Unfortunately, since the launch of AquaCrop in 2009, only tef and barley have been added to the original database of 12 crops. Currently, most important cereals (maize, wheat, barley, rice and sorghum) and some important tubers (potato and sugar beet) are included, but vegetable crops are under-represented (only tomato), and grasses or trees completely absent. Also the model comparison study by Hunink et al. (2011) mentions that availability of pre-calibrated crops is poorer for AquaCrop than for other agro-hydrological models including APSIM, CropSyst, DSSAT, STICS, SWAP, SWAT and WOFOST. The database of SWAT, for example, includes more than 60 different crops, with multiple parameter sets for different varieties. Clearly, the AquaCrop research community should focus its efforts on developing new crop parameter sets. The Food and Agriculture Organization (FAO), being the model developer, should facilitate collaboration between different research groups in order to validate the published local parameter sets (listed by Shrestha et al., 2016) over a wide range of environmental conditions. Only then, a solid set of conservative parameters can be obtained for inclusion in the AquaCrop database. In addition, it would be practical if the AquaCrop database contained a parameter set for simulation of a bare soil with no canopy cover. Such a crop file would facilitate simulation of extensive crop rotations including periods with bare soils as presented in Chapter 6 and 7.

Notwithstanding AquaCrop-Hydro's low data and calibration requirements, this research confirmed that AquaCrop-Hydro can simulate crop production and water availability, as well as the effect of agricultural management and environmental changes, with reasonable accuracy.

First, Chapter 6 illustrated that AquaCrop-Hydro can simulate both crop production and water availability with acceptable accuracy. Crop yield in the Plankbeek catchment was estimated with a relative root-mean-square error (RRMSE) between 7 and 36.5%, depending on the crop type. Also, discharge at the catchment outlet was simulated with satisfactory accuracy (model efficiency (EF) of 0.64) on a daily basis and high accuracy on a 10-day or monthly basis (EF of 0.82).

Second, Chapter 3 and 4 clearly illustrated the model's good balance between data requirements and accuracy for simulating the effect of agricultural management on the soil water balance, crop development and production at field scale. After calibrating the crop response to soil fertility stress based on easily obtainable inputs, the effect of soil fertility management can be simulated with a single input parameter, i.e. relative biomass production (B_{rel}). Also for weed management only two easily observable input parameters are required, i.e. the relative weed cover (RC) and weed-induced increase of total canopy cover ($\mathrm{f_{weed}}$). Nevertheless, crop production was simulated with a RRMSE between 4 and 26% for five different crops (wheat, barley, maize, quinoa, tef) cultivated under various environmental conditions and different soil fertility, weed and water management treatments. In addition, AquaCrop performed very good for simulation of the soil water content in the root zone of these cropping systems, with RRMSE values of between 4.5 and 13.5%. Model comparison in Chapter 3 and Box 4.1 showed that, despite its simple approach to simulate the impact of soil fertility stress or weed infestation, AquaCrop performs at least as good as other models.

Finally, Chapter 7 illustrated that by straightforward adaptation of climate and management inputs, the effect of climate change and related management adaptations is simulated realistically. Although AquaCrop-Hydro's simulation results could not be directly validated to field observations, the projected agro-hydrological impact of climate change was in line with results of other simulation studies. Only the simulated crop responses to future weather conditions were not always as one would expect based on historical observations. This is caused by the above discussed limitations of AquaCrop to accurately simulate crop responses to water and (extreme) temperature stress.

Criterion 4: The model is widely applicable, to various environmental conditions and cropping systems as well as agricultural catchments with different characteristics

Assessment: Due to the wide applicability of both submodels, AquaCrop-Hydro fulfils this fourth criterion.

This research validated AquaCrop-Hydro for a single agricultural catchment, the Plankbeek catchment, in temperate Belgium (Chapter 6). Obviously, only validation for a wide range of agricultural catchments with varying characteristics can confirm that AquaCrop-Hydro is widely applicable. In particular, validation for drought-prone regions with rainfed cropping systems is important as those are the key areas for upgrading crop water productivity with improved agricultural management. Also, validation for data-scarce regions is needed to ensure that the model is applicable when few data are available, which is often the case in developing countries. Nevertheless, one can be confident that AquaCrop-Hydro is indeed widely applicable, because of the wide applicability of its submodels.

First, the list of publications composed by Van Gaelen (2016a) shows that AquaCrop has been applied to different cropping systems in more than 45 countries. These include developed countries such as USA (Hsiao et al., 2009; Heng et al., 2009), Australia (Zeleke et al., 2011) and Belgium (Vanuytrecht et al., 2014c), as well as developing countries such as Ethiopia (Abrha et al., 2012; Tsegay et al., 2012), Burkina Faso (Wellens et al., 2013), Iran (Andarzian et al., 2011), Bolivia (Geerts et al., 2009a) and Nepal (Shrestha et al., 2013b). The studied cropping systems cover a wide range of environmental conditions (arid to humid, tropical to temperate climatic conditions and various soil types), agronomic management practices (rainfed versus irrigated agriculture, various crop and field management practices) and crop types. AquaCrop has been applied for more than 30 different crops. These include widely cultivated crops such as barley, maize, wheat and rice (García-Vila et al., 2009; Heng et al., 2009; Andarzian et al., 2011; Abrha et al., 2012; Shrestha et al., 2013b), but also under-utilized crops such as quinoa, tef and bambara groundnut (Geerts et al., 2009b; Tsegay et al., 2012; Karunaratne et al., 2011). In addition, this research confirmed AquaCrop's wide applicability as the model was applied to 14 different crops, cultivated at nine locations with various agronomic and environmental conditions in seven different countries.

Second, also conceptual models defined according to the VHM approach by Willems (2014) have been applied to catchments in different countries, including Belgium (Van Steenbergen and Willems, 2012; Willems et al., 2014), Ecuador (Mora Serrano, 2013), China (Liu et al., 2011), Uganda (Nyeko-Ogiramoi et al., 2010), Kenya and Ethiopia (Taye et al., 2011). Catchments varied in climatic conditions, topography, soil types, land use and ecosystems. Catchment size ranged between 30 and 15.000 km^2, but Chapter 6 shows that the VHM approach is also applicable to very small catchments such as the Plankbeek catchment (4.5 km^2). Furthermore, the simple and flexible model structure of VHM conceptual models ensures that they are widely applicable to catchments with varying characteristics. Model components can be easily added or discarded depending on whether they are important in the study area and their properties identifiable from the available data.

8.2 Model usability

AquaCrop-Hydro does not only meet the four criteria to a large extent, but has the additional benefit of being a practical tool. It was demonstrated by the extensive scenario analyses in Chapter 5 and Chapter 7 that AquaCrop-Hydro allows efficient analysis of several agricultural management scenarios for various environmental conditions. This efficiency stems from the short data processing and model execution time.

Processing of the model input and calibration data is facilitated by AquaCrop-Hydro's low data and calibration requirements, as discussed above. In addition, the AquaCrop software containes a graphical user-interface to assist in preparation of input data files. Moreover, the AquaData tool or AquaCrop-GIS frameworks (Lorite et al., 2013; Thorp and Bronson, 2013) can speed up data processing for extensive simulation studies that require a large number of simulations for several locations or scenarios. Unfortunately, the use of earth observation data as model input (data assimilation) is not yet possible in AquaCrop. But, future model development will enable updating simulation results according to observed canopy cover, soil water content and biomass.

Including AquaCrop as a submodel, increases internal data-processing time because AquaCrop's protected source code impedes direct model linkage. The AquaCrop calculation procedures for simulation of the soil water balance and crop production at field scale could not be directly implemented in the AquaCrop-Hydro Matlab code that was developed in the framework of this research (Van Gaelen, 2016b). Instead, the Matlab script invokes an AquaCrop simulation for each land unit and extracts the required data from the AquaCrop output files. These data are subsequently used for simulating the catchment soil water balance and discharge at the catchment outlet. Obviously, this off-line linkage of the two submodels results in additional internal data-processing and consequently increases execution times of AquaCrop-Hydro.

Despite the inefficient off-line linkage between AquaCrop and the hydrological submodel, model execution times of AquaCrop-Hydro are small. This is certainly the case when AquaCrop simulations are done using the AquaCrop plug-in software, which executes the model without a graphical user-interface. Chapter 6 demonstrated that a 15 year long AquaCrop-Hydro simulation for the Plankbeek catchment (31 land units) took less than four minutes using the Matlab code by Van Gaelen (2016b) in combination with the AquaCrop plug-in on a standard computer. This is significantly faster than the execution of the ArcNemo model for the same catchment (Van Opstal, personal communication) and typical SWAT executions for similar catchments (Yalew et al., 2013).

8.3 Model application and limitations

Next to being a practical tool, AquaCrop-Hydro has expanded the application domain of both of its submodels.

On the one hand, AquaCrop-Hydro has upgraded AquaCrop's evaluation of agricultural management from field to catchment scale. This cross-scale evaluation ensures that the trade-offs that arise when agricultural management affects water allocation within the catchment can be taken into account during the decision making process. More specifically, AquaCrop-Hydro reveals the trade-off between increasing crop (water) productivity at field scale and controling water availability at catchment scale. This is crucial, because Molden et al. (2010) report that increases in water productivity at farm level can increase basin water depletion. Conversely, Kijne et al. (2009) mention that increasing crop water productivity might lead to a reduction of water withdrawal for supplemental irrigation which positively affects water availability in the region. Also, the AquaCrop-Hydro simulation study for the Plankbeek catchment (Chapter 7) demonstrated that adapted agricultural management increased crop yield and water productivity under future climatic conditions and at the same time increased water availability during dry summer months.

On the other hand, AquaCrop-Hydro has not only up-scaled evaluation of agricultural management, but also down-scaled investigation of large scale environmental changes (e.g. climate change) to the scale of individual land units. The simulation study in Chapter 7 revealed how the complex effect of climate change on the plant-soil system also influences the overall effect of climate change on the agricultural catchment. Indeed, climate change has a direct impact on the catchment water balance because of altered weather conditions, but on top of that it affects the water balance because of its effect on crop growth, evapotranspiration and farmers' management decisions.

Furthermore, although this research showed that AquaCrop-Hydro can be used to investigate a wide range of agricultural management practices, the model is especially strong to evaluate water management, both in rainfed and irrigated cropping systems. As compared to other crop-centred agro-hydrological models, such as SWAT, AquaCrop-Hydro contains a more detailed description of crop responses to water stress (Chapter 6) due to the water-driven nature of the AquaCrop submodel. Also, accurate simulation of the soil water balance and irrigation management practices is one of AquaCrop's strengths as compared to other models (Hunink et al., 2011). Even though this research focussed on rainfed agriculture, AquaCrop-Hydro shows potential to be used for optimizing irrigation management with consideration of water availability in the area.

Despite these good prospects for application of AquaCrop-Hydro, this research also identified some limitations. Although some of these limitations might be solved by future model developments, they should be considered when applying the current model structure.

First, it was already mentioned in Section 8.1 (criterion 1) that the daily time step of AquaCrop-Hydro restricts its use for flood modelling studies. However, the goal of this research was to develop an agro-hydrological model that can evaluate the effect of agricultural management on large scale water availability, rather than instantaneous river discharge volumes. For the postulated purpose, a good estimate of river discharge at 10-day or monthly time step, which AquaCrop-Hydro can provide as shown in Chapter 6, is sufficient. Also the impact assessment in Chapter 7 showed that analysis of monthly discharge volumes at the catchment outlet already provides useful information regarding the impact of agricultural management practices for climate change adaptation.

Second, the consequences of AquaCrop-Hydro not being a fully distributed model for simulation accuracy have been discussed above in Section 8.1 (criterion 1). In addition, the lack of a spatially distributed description of the soil water balance or transport of water within the catchment also has its limitations for model application. AquaCrop-Hydro can not be used for spatial planning of implementation of agricultural management practices. The effect of tied ridges on surface runoff and water availability can be studied as done in Chapter 7, but it is impossible to define on which locations these tied ridges should preferably be constructed. To study water transport over land or in the river a fully distributed model such as MIKE-SHE linked to the MIKE 11 river model (DHI, 2016) would be more suited. Nevertheless, MIKE SHE's basic representation of land use, vegetation and agricultural management might be a limitation.

Third, it was found in Chapter 6 that with the current model structure AquaCrop-Hydro should be used with caution when agricultural catchments contain a high proportion of:

- **Groundwater-dominated soils:** As discussed in Section 8.1 (criterion 1), AquaCrop-Hydro's poor description of the two-directional interaction between the unsaturated and saturated zone, makes model use infeasible and simulations of the soil water balance and hydrological processes inaccurate when a large area of the catchment has a shallow groundwater table.

- **Winter crops:** As discussed in Section 8.1 (criterion 2), the current AquaCrop simulation procedures lead to inaccurate simulation of development and production of winter crops. Consequently, the poor estimation of evapotranspiration also affects the simulated soil water balance and water availability of catchments containing a large proportion of winter crops.

- **Grassland and fodder crops:** Although about 75% of the world's agricultural area is covered by pasture and fodder crops (FAO, 2008), AquaCrop is not able to accurately simulate development and production of these crop types. First intents to use AquaCrop for simulation of alfalfa have been made by Kim and Kaluarachchi (2015), and the obtained crop parameters were also applied in this research to simulate grassland and cover crops in the Plankbeek catchment (Chapter 6-7). However, to improve simulation accuracy for crop canopy development and production, new calculation procedures need to be introduced. These procedures need to deal with the perennial character of these crop types, carry-over effects across different production seasons, as well grazing or cutting which reduces the crop canopy cover (Holzworth et al., 2015; Snow et al., 2014).

- **Perrenial trees and woody crops:** AquaCrop was developed for simulation of herbaceous crops, but not woody crops or trees. Nevertheless, the model has been used to estimate evapotranspiration of olive tree (Rallo et al., 2012) and jatropha (Segerstedt and Bobert, 2013). The model also seems promising for estimation of leaf or wood biomass production, as shown by studies for tea (Elbehri et al., 2015) and short rotation poplar plantations (Horemans et al., 2016). However, new procedures need to be implemented to deal with the perennial character of woody crops and trees, as well as the effect of biomass harvesting. Furthermore, it seems very unlikely that AquaCrop could obtain good results for fruit trees, as fruit formation is a highly complex process affected by tree pruning and weather conditions over several years which is not yet well understood (Steduto et al., 2012).

Fourth, due to the off-line linkage between both submodels, the interaction between the field and catchment scale hydrological processes is one-directional. This issue was already raised when discussing the poorly simulated interaction between the saturated and unsaturated zone in Section 8.1 (criterion 1). However, the off-line linkage also affects application of AquaCrop-Hydro for design and evaluation of irrigation management strategies. While the effect of irrigation management on catchment water availability can be simulated with

AquaCrop-Hydro, the opposite is not true. Currently, simulated irrigation schedules need to be manually checked and updated so that the water requirements match catchment water availability. The model does not include a direct feedback mechanisms that could update irrigation applications according to water availability in the river or groundwater reservoir. Obviously, for evaluation of rainfed agricultural management strategies, which has been the focus of this research, the one-directional linkage between field and catchment scale is not an issue.

Finally, AquaCrop-Hydro can not provide a fully integrated assessment of land and water resources management. The current model structure is definitely a first step towards evaluation of environmental changes and management actions across scales and research domains. Nevertheless, further integration of additional aspects related to agricultural management and its regional impact is required to conduct a fully integrated assessment of agricultural management practices. These include, for example, evaluation of the socio-economic feasibility of agricultural management practices and their effect on water quality (not just water quantity) and ecosystem services.

However, upgrading AquaCrop-Hydro to a fully integrated assessment model, that considers all socio-economic and environmental aspects of land and water resources management within a catchment, inevitably leads to loss of model simplicity, transparency and applicability. A better option would be to link AquaCrop-Hydro to additional models by means of a flexible modelling framework, in which model components can be added or removed according to the desired application. Unfortunately, the current generation of agro-hydrological models are rarely designed with attention for model reuse or linkage functionality. As such, their incorporation in large modelling frameworks is tedious. Clearly, the modelling community faces the challenge to develop models that (i) are open-source, (ii) are well documented, (iii) use standard data formats, and (iv) have a flexible model structure which consists of small independent modules that can easily be reused (Laniak et al., 2013; Holzworth et al., 2015; Bergez et al., 2012).

The release of an open-source AquaCrop code by FAO would be an important step in that direction. Especially, when this model code is composed of small reusable model components, like the AquaCrop code currently being implemented in the BioMA (Biophysical Models Applications) platform (European Commission, 2016). An open-source Matlab code of AquaCrop has recentely been developed by Foster et al. (2016). Because of its compatibility, this open-source code seems an excellent candidate for incorporation in the AquaCrop-Hydro Matlab code (Van Gaelen, 2016b). This would not only reduce the model's execution time, but also facilitate further model development. In addition, it would promote linking AquaCrop-Hydro to other models in a fully integrated modelling framework. Only then, AquaCrop-Hydro can reach its full potential and contribute to support decisions regarding agricultural management, taking into account different spatial and temporal scales as well as multiple stakeholders with varying goals and incentives that share the precious natural resources.

8.4 General conclusion

AquaCrop-Hydro appears to be a parsimonious, widely applicable model that is able to evaluate the agro-hydrological impact of agricultural management from field to catchment scale. Hence, the developed model meets the targeted characteristics and consequently fills an important gap in the range of existing agro-hydrological models. With the current model structure, AquaCrop-Hydro can be used to evaluate the effect of agricultural management and environmental changes on crop development, crop production, crop water productivity, the soil water balance and water availability in agricultural catchments. Nevertheless, there is room to improve model accuracy, functionality and expand the application domain. Future model development could improve simulation of the interaction between the saturated and unsaturated zone for groundwater-dominated catchments. Also, revision of the surface runoff calculation procedures might enable model application for flood investigation. In addition, AquaCrop-Hydro would benefit from further developments of the AquaCrop submodel. Priority should be given to (i) improvement of simulation procedures describing crop responses to water and (extreme) temperature stress, (ii) addition of procedures to improve simulation of winter crops, grassland, forage and woody crops, and (iii) addition of new crops, especially vegetable crops, to the AquaCrop crop database. Finally, releasing the AquaCrop source code is a prerequisite for further development of AquaCrop-Hydro, as well implementation of AquaCrop-Hydro in an extensive modelling framework to support fully integrative water and land resource management.

Appendix A

AquaCrop parameters

Table A.1: Default soil parameter values for various USDA soil textural classes in AquaCrop version 4.0 and AquaCrop version 5.0. Default values for soil water content at saturation (θ_{SAT}), field capacity (θ_{FC}) and wilting point (θ_{PWP}) as well as readily evaporable water (REW) are equal for all AquaCrop versions. Default values for saturated hydraulic conductivity (K_{sat}) and surface runoff curve numbers (CN) differ between AquaCrop version 4.0 and version 5.0.

	All versions				**Version 4.0**		**Version 5.0**	
Texture	θ_{SAT} (vol%)	θ_{FC} (vol%)	θ_{PWP} (vol%)	**REW** (mm)	$\mathbf{K_{sat}}$ (mm/day)	**CN** (-)	$\mathbf{K_{sat}}$ (mm/day)	**CN** (-)
Sand	36	13	6	4	1500	65	3000	46
Loamy sand	38	16	8	5	800	65	2200	46
Sandy loam	41	22	10	7	500	65	1200	46
Loam	46	31	15	9	250	65	500	61
Silt loam	46	33	13	11	150	75	575	61
Silt	43	33	9	11	50	75	500	61
Sandy clay loam	47	32	20	9	125	75	225	72
Clay loam	50	39	23	11	100	75	125	72
Silty clay loam	52	44	23	13	120	75	150	72
Sandy clay	50	39	27	10	75	75	35	77
Silty clay	54	50	32	14	15	80	100	72
Clay	55	54	39	14	2	85	35	77
Impermeable	0.5	0.3	0.1	0	0	85	0	77

Table A.2: Conservative (c) and non-conservative (nc) AquaCrop crop parameters that describe crop growth, transpiration and production under non-limiting conditions (nl), as well as conditions with elevated CO_2 concentrations (co), water (w), temperature (t), soil fertility (f) and soil salinity (s) stress.

Parameter	Description	Units	Type	Conditions
Settings				
m	Determination of crop cycle by calendar days (1) or by growing degree days (0)			
sow	Crop is sown (1) or transplanted (2)			
typ	Crop type (1= leafy vegetable crop, 2 = fruit/grain producing, 3 = root/tuber)			
det	Crop determinancy linked (1) or unlinked (0) with flowering			
Canopy development				
ccs	Soil surface covered by an individual seedling at 90% emergence	cm^2	c	nl
cdc	Decrease in canopy cover	m^2/m^2 GDD or m^2/m^2 d	c	nl
cgc	Increase in canopy cover	m^2/m^2 GDD or m^2/m^2 d	c	nl
CC_x	Maximum canopy cover	m^2/m^2	nc	nl
den	Number of plants per hectare	plants/ha	nc	nl
eme	Period from sowing to emergence	GDD or d	nc	nl
mat	Total length of crop cycle from sowing to maturity	GDD or d	nc	nl
sen	Period from sowing to start senescence	GDD or d	nc	nl
etos	ET_0-sum to be exceeded during stress period before senescence is triggered	mm	c	w
pexlw	Soil water depletion factor for canopy expansion - lower threshold		c	w
pexshp	Shape factor for water stress coefficient for canopy expansion (0.0 = straight line)		c	w
pexup	Soil water depletion factor for canopy expansion - upper threshold		c	w
psen	Soil water depletion factor for canopy senescence - upper threshold		c	w
psenshp	Shape factor for water stress coefficient for canopy senescence (0.0 = straight line)		c	w
tb	Base temperature below which crop development does not progress	°C	c	t

Table A.2 Cont.: Conservative (c) and non-conservative (nc) AquaCrop crop parameters that describe crop growth and production under non-limiting conditions (nl), as well as conditions with elevated CO_2 concentrations, water (w), temperature (t), soil fertility (f) and soil salinity (s) stress.

Parameter	Description	Units	Type	Conditions
tup	Upper temperature above which crop development no longer increases with an increase in temperature	°C	c	t
sccxshp	Shape factor for soil fertility/salinity stress coefficient for maximum canopy cover		nc	f/s
sdecshp	Shape factor for the response of decline of canopy cover to soil fertility/salinity stress		nc	f/s
sexshp	Shape factor for soil fertility/salinity stress coefficient for canopy expansion		nc	f/s
Evapotranspiration				
evardc	Effect of canopy cover in reducing soil evaporation in late season stage		c	nl
kcdcl	Decline of crop transpiration coefficient as a result of ageing and senescence	%/day	c	nl
kcx	Maximum crop transpiration coefficient when canopy is complete but prior to senescence		c	nl
psto	Soil water depletion fraction for stomatal control - upper threshold		c	w
pstoshp	Shape factor for water stress coefficient for stomatal control (0.0 = straight line)		c	w
anaer	Anaerobic point at which deficient aeration occurs	vol% below θ_{SAT}	nc	w
sstoshp	Shape factor for soil salinity stress coefficient for stomatal closure		nc	s
Biomass production				
fwpy	Ratio of water productivity normalized for ET_0 and CO_2 during yield formation	%	c	nl
wp*	Crop water productivity normalized for ET_0 and CO_2	g/m^2	c	nl
f_{sink}	Crop performance under elevated atmospheric CO_2 concentration	%	nc	co
stbio	Minimum growing degrees required for full biomass production	°C/d	c	t
swpshp	Shape factor for soil fertility stress coefficient for crop water productivity		nc	f
ecmx	Maximum electrical conductivity of saturated soil-paste extract at which crop can no longer grow	dS/m	c	s
ecmn	Minimum electrical conductivity of saturated soil-paste extract at which crop starts to be affected by soil salinity	dS/m	c	s

Table A.2 Cont.: Conservative (c) and non-conservative (nc) AquaCrop crop parameters that describe crop growth and production under non-limiting conditions (nl), as well as conditions with elevated CO_2 concentrations, water (w), temperature (t), soil fertility (f) and soil salinity (s) stress.

Parameter	**Description**	**Units**	**Type**	**Conditions**
sbshp	Shape factor for soil salinity stress coefficient for biomass production		nc	s
Yield formation				
exc	Excess of potential fruits	%	c	nl
hilen	Period of harvest index building-up during yield formation	GDD or d	c	nl
hio	Reference harvest index	%	c	nl
flo	Period from sowing to flowering/tuber formation	GDD or d	nc	nl
flolen	Length of flowering	GDD or d	nc	nl
polmn	Minimum air temperature below which pollination starts to fail (cold stress)	°C	c	t
polmx	Maximum air temperature above which pollination starts to fail (heat stress)	°C	c	t
hinc	Allowable maximum increase of specified harvest index	%	c	w
hingsto	Coefficient describing negative impact on harvest index of stomatal closure during yield formation		c	w
hipsflo	Possible increase of harvest index due to water stress before flowering	%	c	w
hipsveg	Coefficient describing positive impact on harvest index of restricted vegetative growth during yield formation		c	w
ppol	Soil water depletion factor for pollination - upper threshold		c	w
Root zone development				
rtshp	Shape factor describing root zone expansion		c	nl
root	Period from sowing to maximum rooting depth	GDD or d	nc	nl
rtexlw	Maximum root water extraction in bottom quarter of root zone	m^3/m^3soil d	nc	nl
rtexup	Maximum root water extraction in top quarter of root zone	m^3/m^3soil d	nc	nl
rtx	Maximum effective rooting depth	m	nc	nl
rtn	Minimum effective rooting depth	m	nc	nl

Table A.3: Default crop parameter values in AquaCrop version 4.0 for the studied crops of Chapter 3-5.

Parameter	Units	Wheat	Wheat GDD	Barley	Barley GDD	Maize	Maize GDD	Tef	Quinoa
typ		2	2	2	2	2	2	2	2
sow		1	1	1	1	1	1	1	1
m		1	0	1	0	1	0	1	1
tb	°C	0	0	0	0	8	8	10	2
tup	°C	26	26	15	15	30	30	30	30
pexup		0.2	0.2	0.2	0.2	0.14	0.14	0.32	0.5
pexlw		0.65	0.65	0.65	0.65	0.72	0.72	0.66	0.8
pexshp		5	5	3	3	2.9	2.9	3	4
psto		0.65	0.65	0.6	0.6	0.69	0.69	0.6	0.6
pstoshp		2.5	2.5	3	3	6	6	3	4
psen		0.7	0.7	0.55	0.55	0.69	0.69	0.58	0.98
psenshp		2.5	2.5	3	3	2.7	2.7	3	4
etos	mm	0	0	0	0	0	0	0	200
ppol		0.85	0.85	0.85	0.85	0.8	0.8	0.92	0.85
anaer	vol% below θ_{SAT}	5	5	15	15	5	5	6	10
polmn	°C	5	5	5	5	10	10	8	-9
polmx	°C	35	35	35	35	40	40	40	-9
stbio	°C/d	14	14	14	14	12	12	11.1	-9
kc		1.1	1.1	1.1	1.1	1.05	1.05	1.1	1.1
kcdcl	%/d	0.15	0.15	0.15	0.15	0.3	0.3	0.3	0.15
rtn	m	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3
rtx	m	1.5	1.5	1.3	1.3	2.3	2.3	0.6	1
rtshp		15	15	15	15	13	13	15	15
rtexup	m^3/m^3soil d	0.028	0.028	0.019	0.019	0.01	0.01	0.023	0.024
rtexlw	m^3/m^3soil d	0.008	0.008	0.006	0.006	0.003	0.003	0.008	0.006
evardc		50	50	50	50	50	50	60	60
ccs	cm^2	1.5	1.5	1.5	1.5	6.5	6.5	0.25	6.5
den	plants/ha	4500000	4500000	1500000	1500000	75000	75000	10000000	200000

Table A.3 Cont.: Default crop parameter values in AquaCrop version 4.0 for the studied crops of Chapter 3-5

Parameter	Units	Wheat	Wheat GDD	Barley	Barley GDD	Maize	Maize GDD	Tef	Quinoa
CC_x	m^2/m^2	0.96	0.96	0.8	0.8	0.96	0.96	0.81	0.75
det		1	1	1	1	1	1	1	0
exc	%	100	100	100	100	50	50	50	50
wp*	g/m^2	15	15	15	15	33.7	33.7	14	10.5
fwpy	%	100	100	100	100	100	100	100	90
f_{sink}	%	50	50	50	50	50	50	50	50
hio	%	48	48	33	33	48	48	27	50
hipsflo	%	5	5	5	5	0	0	0	0
hipsveg		10	10	10	10	7	7	0.5	-9
hingsto		7	7	5	5	3	3	10	9
hinc	%	15	15	15	15	15	15	40	10
eme	GDD or d	13	150	7	98	6	80	14	7
root	GDD or d	93	864	60	854	108	1409	55	83
sen	GDD or d	158	1700	65	924	107	1400	75	160
mat	GDD or d	197	2400	93	1296	132	1700	99	180
flo	GDD or d	127	1250	60	867	66	880	55	70
flolen	GDD or d	15	200	12	160	13	180	11	20
cgc	m^2/m^2 GDD or m^2/m^2 d	0.04901	0.005001	0.1241	0.008697	0.16312	0.012494	0.14644	0.1
cdc	m^2/m^2 GDD or m^2/m^2 d	0.07179	0.004	0.07697	0.006	0.11691	0.01	0.116	0.1
hilen	GDD or d	67	1100	27	351	61	750	40	90

Appendix B

Plankbeek catchment

Table B.1: The 47 land units (LUs) together with their percentage of the Plankbeek catchment area, land use, soil type and crop rotation (main season and after season crop). LUs with the same simulation number were ran by a single simulation.

LU	Sim	Land use	Main Crop	After crop	Soil	Area (%)
1	1	Open water	Bare soil	Bare soil	Silt Loam	0.7
2	2	Impervious	Bare soil	Bare soil	Silt Loam	0.2
3	3	Forest	Deciduous forest	Bare soil	Silt Loam	5.2
4	4	Agriculture	Winter wheat	Bare soil	Sandy loam	0.4
5	5	Agriculture	Winter wheat	Bare soil	Silt loam	7.9
6	6	Agriculture	Winter wheat	Cover crop	Sandy loam	0.5
7	7	Agriculture	Winter wheat	Cover crop	Silt loam	9.9
8	8	Agriculture	Winter barley	Bare soil	Sandy loam	0.0
9	9	Agriculture	Winter barley	Bare soil	Silt loam	0.6
10	10	Agriculture	Winter barley	Cover crop	Sandy loam	0.0
11	11	Agriculture	Winter barley	Cover crop	Silt loam	0.8
12	12	Agriculture	Maize (grain)	Bare soil	Sandy loam	0.3
13	12	Agriculture	Maize (forage)	Bare soil	Sandy loam	0.2
14	13	Agriculture	Maize (grain)	Bare soil	Silt loam	6.0
15	13	Agriculture	Maize (forage)	Bare soil	Silt loam	4.8
16	14	Agriculture	Maize (forage)	Grassland	Sandy loam	0.1
17	15	Agriculture	Maize (forage)	Grassland	Silt loam	2.2
18	16	Agriculture	Sugar beet	Bare soil	Sandy loam	0.5
19	17	Agriculture	Sugar beet	Bare soil	Silt loam	9.7
20	16	Agriculture	Fodderbeet	Bare soil	Sandy loam	0.0
21	17	Agriculture	Fodderbeet	Bare soil	Silt loam	0.4
22	18	Agriculture	Potato	Bare soil	Sandy loam	0.7
23	19	Agriculture	Potato	Bare soil	Silt loam	14.4
24	20	Agriculture	Green beans	Bare soil	Sandy loam	0.1
25	21	Agriculture	Green beans	Bare soil	Silt loam	1.4
26	22	Agriculture	Peas	Bare soil	Sandy loam	0.1
27	23	Agriculture	Peas	Bare soil	Silt loam	2.9
28	24	Agriculture	Peas	Cover crop	Sandy loam	0.2
29	25	Agriculture	Peas	Cover crop	Silt loam	3.1
30	26	Agriculture	Carrot	Bare soil	Sandy loam	0.1
31	27	Agriculture	Carrot	Bare soil	Silt loam	1.3
32	26	Agriculture	Chicory	Bare soil	Sandy loam	0.1
33	27	Agriculture	Chicory	Bare soil	Silt loam	2.7
34	28	Agriculture	Grassland	Bare soil	Sandy loam	0.2

Table B.1 Cont.: The 47 land units (LUs) together with their percentage of the Plankbeek catchment area, land use, soil type and crop rotation (main season and after season crop). LUs with the same simulation number were ran by a single simulation.

LU	Sim	Land use	Main Crop	After crop	Soil	Area (%)
35	29	Agriculture	Grassland	Bare soil	Silt loam	4.7
36	30	Agriculture	Grassland	Grassland	Sandy loam	0.5
37	31	Agriculture	Grassland	Grassland	Silt loam	11.1
38	28	Agriculture	Clover	Bare soil	Sandy loam	0.0
39	29	Agriculture	Clover	Bare soil	Silt loam	0.3
40	30	Agriculture	Clover	Clover	Sandy loam	0.0
41	31	Agriculture	Clover	Clover	Silt loam	0.4
42	28	Agriculture	Grass-clover	Bare soil	Sandy loam	0.0
43	29	Agriculture	Grass-clover	Bare soil	Silt loam	0.2
44	30	Agriculture	Grass-clover	Grass-Clover	Sandy loam	0.0
45	31	Agriculture	Grass-clover	Grass-Clover	Silt loam	0.5
46	-	Agriculture	Other	Other	Sandy Loam	0.2
47	-	Agriculture	Other	Other	Silt Loam	4.2

Table B.2: Surface runoff curve numbers (CN) for all simulated land use - soil - crop type combinations in the Plankbeek catchment, Flanders, Belgium. The CN values are valid under the assumption that the initial abstraction equals 5% of the surface storage capacity.

Land use	Soil texture	Crop type	CN
Impervious	Silt loam	N/A	98
Forest	Silt loam	Deciduous trees	46
Agriculture	Silt loam	Bare soil	81
Agriculture	Silt loam	Maize	72
Agriculture	Silt loam	Other cereals	65
Agriculture	Silt loam	Vegetables	67
Agriculture	Silt loam	Roots / tubers	72
Agriculture	Silt loam	Forage crops	47
Agriculture	Silt loam	Grassland	57
Agriculture	Sandy loam	Bare soil	68
Agriculture	Sandy loam	Maize	60
Agriculture	Sandy loam	Other cereals	51
Agriculture	Sandy loam	Vegetables	52
Agriculture	Sandy loam	Roots / tubers	60
Agriculture	Sandy loam	Forage crops	24
Agriculture	Sandy loam	Grassland	34

Table B.3: Crop parameters for all simulated crops in the Plankbeek catchment, Flanders, Belgium.

Parameter	Units	Winter wheat	Winter barley	Maize	Sugar beet	Potato	Peas	Carrot	Green beans	Grassland	Deciduous forest
typ		2	2	2	3	3	2	3	2	1	1
sow		1	1	1	1	0	1	1	1	1	1
m		0	0	0	0	0	0	0	0	1	1
tb	°C	2	0	8	5	2	0	2	6	2	10
tup	°C	26	15	30	30	26	30	26	30	40	30
pexup		0.2	0.2	0.14	0.2	0.2	0.1	0.1	0.05	0.2	0.2
pexlw		0.65	0.65	0.72	0.6	0.6	0.45	0.45	0.55	0.55	0.55
pexshp		5	3	2.9	3	3	3	3	3	3	3
psto		0.65	0.6	0.69	0.65	0.55	0.45	0.35	0.4	0.55	0.5
pstoshp		2.5	3	6	3	3	3	3	3	3	3
psen		0.7	0.55	0.69	0.75	0.7	0.45	0.45	0.7	0.85	0.85
psenshp		2.5	3	2.7	3	3	3	3	3	3	3
etos	mm	0	0	0	0	0	0	0	0	0	0
ppol		0.85	0.85	0.8	0.8	0.8	0.76	0.8	0.92	0.9	0.9
anaer	vol% below θ_{SAT}	5	15	5	5	5	5	5	5	2	4
polmn	°C	5	5	10	8	-	-	-	-	8	10
polmx	°C	35	35	40	40	-	-	-	-	40	40
stbio	°C/d	8	8	13	9	8	14	8	14	13	-
kc		1.1	1.1	1.05	1.1	1.1	1.1	0.95	1.1	0.85	0.95
kcdcl	%/d	0.15	0.15	0.3	0.15	0.15	0.15	0.15	0.15	0.15	0.15
rtn	m	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	1.5
rtx	m	1.5	1.3	1.1	1	0.6	0.5	0.6	0.6	0.6	1.5
rtshp		15	15	13	15	15	15	15	15	15	13
rtexup	m^3/m^3soil d	0.028	0.019	0.021	0.025	0.088	0.048	0.088	0.04	0.04	0.016
rtexlw	m^3/m^3soil d	0.008	0.006	0.007	0.006	0.022	0.012	0.022	0.01	0.01	0.004
evardc		50	50	50	60	60	60	60	60	60	60
ccs	cm^2	0.75	0.75	6.5	1	20	4.05	0.5	5	5	5
den	plants/ha	2000000	2000000	75000	100000	32000	810000	1000000	300000	300000	100000

Table B.3 Cont.: Crop parameters for all simulated crops in the Plankbeek catchment, Flanders, Belgium.

Parameter	Units	Winter wheat	Winter barley	Maize	Sugar beet	Potato	Peas	Carrot	Green beans	Grassland	Deciduous forest
CC_x	m^2/m^2	0.92	0.92	0.87	0.98	1	0.9	0.95	1	0.9	0.9
det		1	1	1	0	0	0	0	0	0	0
exc	%	100	100	50	-	-	20	-	100	20	20
wp*	g/m^2	18.5	18.5	33.7	17	18.5	14	18.5	15	17	17
fwpy	%	100	100	100	100	100	100	100	100	100	100
f_{sink}	%	0	0	0	50	75	60	60	60	50	50
hio	%	52	33	52	70	90	34	60	22	-	-
hipsflo	%	5	5	0	0	2	-	2	2	-	-
hipsveg		10	10	7	4	-	4	-	0.5	-	-
hingsto		7	5	3	-	10	3	10	10	-	-
hinc	%	15	15	15	20	5	0	5	60	-	-
eme	GDD or d	100	100	50	20	150	30	67	110	0	0
root	GDD or d	1200	1200	1200	617	650	478	488	650	31	26
sen	GDD or d	1550	1550	1100	1450	1550	864	1603	850	170	174
mat	GDD or d	1900	1900	1200	1850	1850	945	1850	870	215	205
flo	GDD or d	1200	1200	650	650	650	302	488	450	0	0
flolen	GDD or d	180	180	180	0	0	300	0	300	0	0
cgc	m^2/m^2 GDD or m^2/m^2 d	0.008	0.008	0.012	0.012	0.009	0.014	0.01	0.014	0.214	0.164
cdc	m^2/m^2 GDD or m^2/m^2 d	0.008	0.008	0.01	0.004	0.008	0.002	0.004	0.002	0.045	0.086
hilen	GDD or d	550	550	500	1100	1100	566	1267	400	-	-

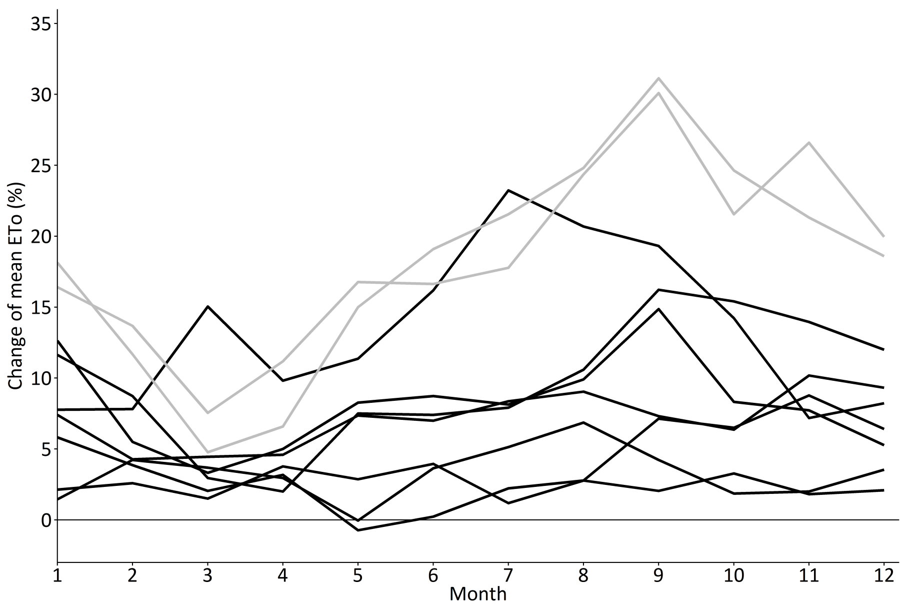


Figure B.1: Relative change of mean reference evapotranspiration (ET_0) in future climatic conditions (2050) with reference to historical conditions (2000) for RCP 8.5 in Belgium. Black lines present the climate signals selected for the climate model ensemble, while grey lines present the additional climate signals that were used to define the synthesized scenarios. A positive value represents an increase of ET_0, while a negative value represents a decrease of ET_0.

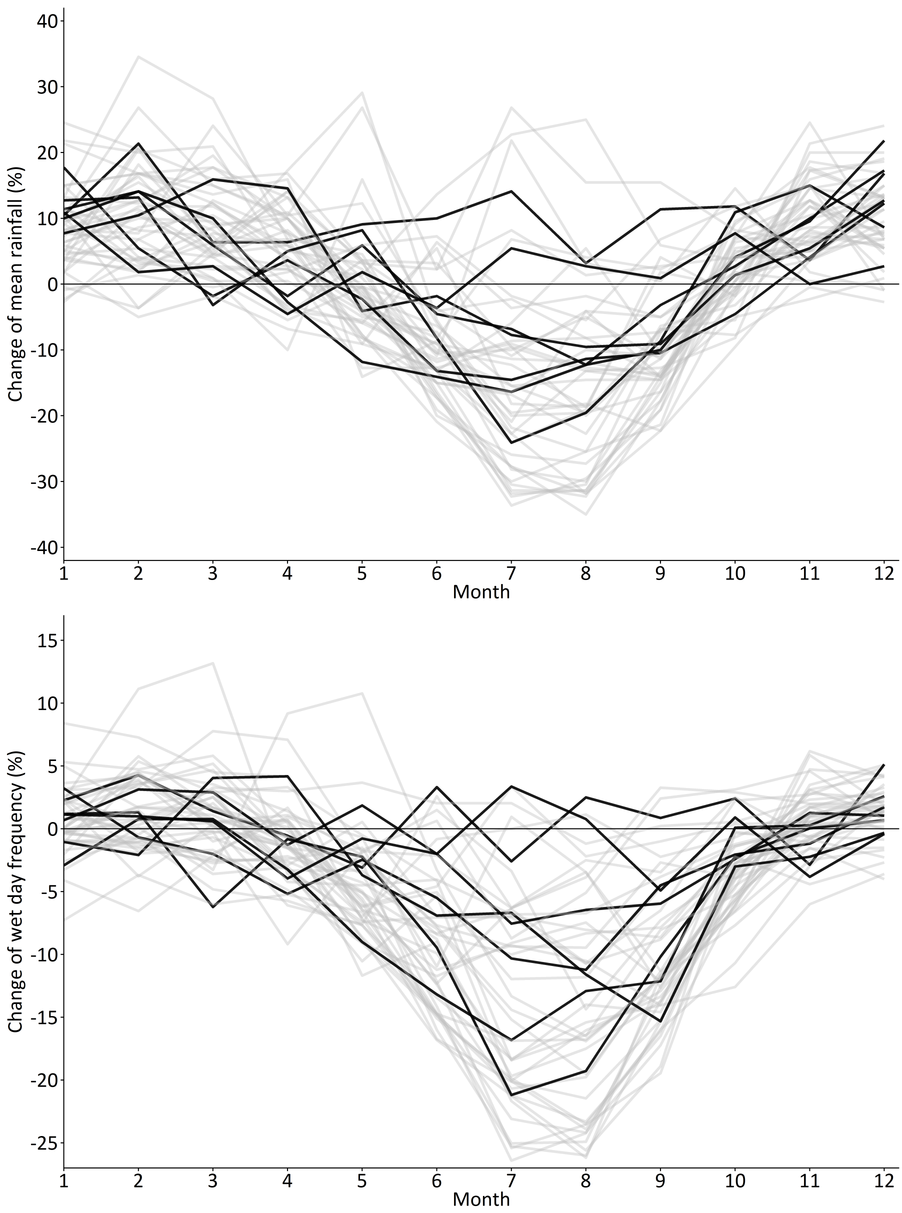


Figure B.2: Relative change of mean monthly rainfall (top) and wet day frequency (bottom) in future climatic conditions (2050) with reference to historical conditions (2000) for RCP 8.5 in Belgium. Black lines present the climate signals selected for the climate model ensemble, while grey lines present the additional climate signals that were used to define the synthesized scenarios. A positive value represents an increase of rainfall amount or frequency, while a negative value represents a decrease of rainfall amount or frequency.

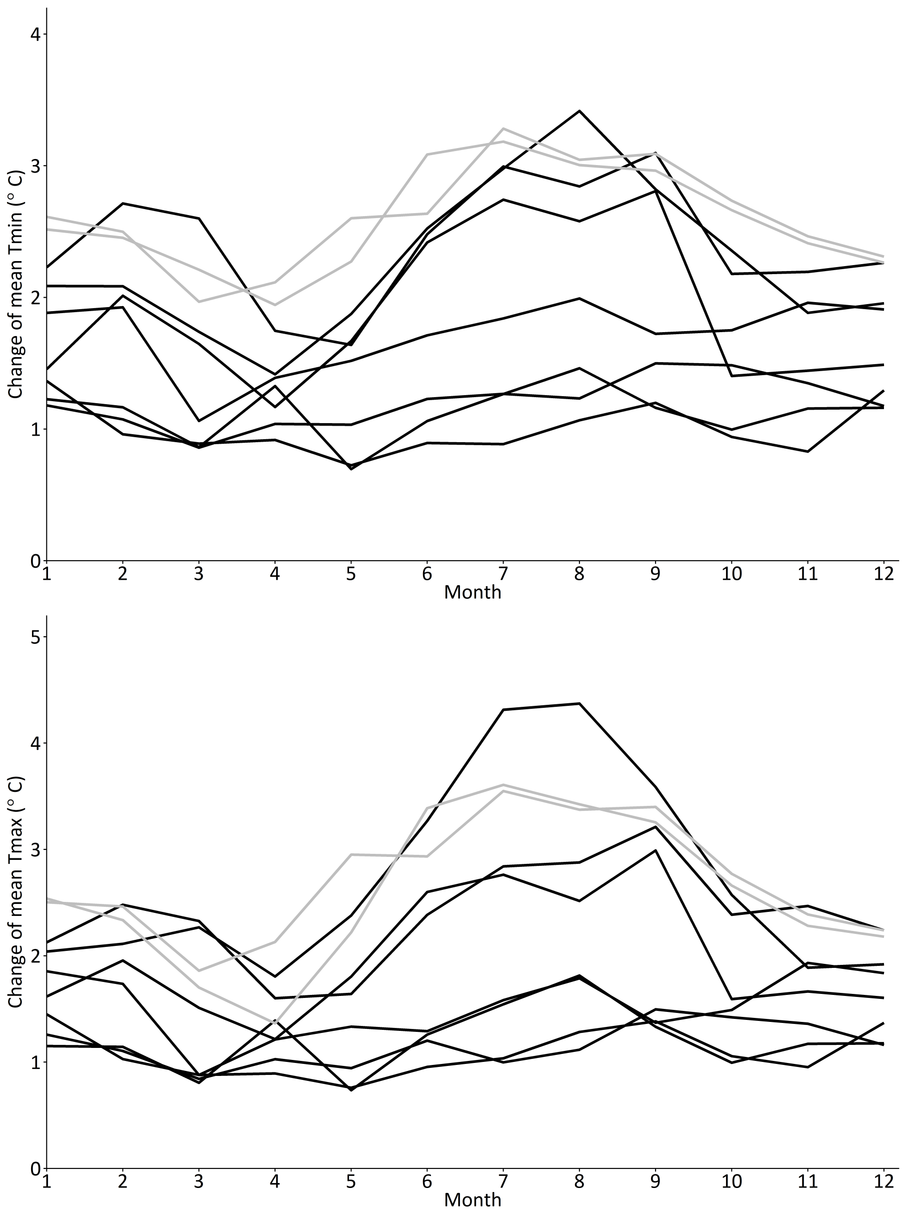


Figure B.3: Absolute change of mean monthly minimum temperature (T_{min}, top) and maximum temperature (T_{max}, bottom) in future climatic conditions (2050) with reference to historical conditions (2000) for RCP 8.5 in Belgium. Black lines present the climate signals selected for the climate model ensemble, while grey lines present the additional climate signals that were used to define the synthesized scenarios. A positive value represents a temperature increase, while a negative value represents a temperature decrease.

Table B.4: Changes in seasonal crop yield, crop water productivity (WP_{ET}), length of the growing period (LGP), water stress index (WSI) and cold stress index (CSI) in 2050 under traditional management as compared to historical conditions (1985-2014) for the Plankbeek catchment (n=30). Presented ranges for future conditions represent the variety between the median values of the 7 GCMs. A positive change value represents an increase, while a negative value represents a decrease.

		Historical median	**Future median change under traditional management**		
			minimum	**median**	**maximum**
Maize					
Yield	(t/ha)	10.19	-1.163	+0.144	+0.478
WP_{ET}	(kg/m^3)	2.64	+0.10	+0.29	+0.35
LGP	(d)	133	-33	-22	-14
WSI	%	4.1	-0.9	-0.2	+6.8
CSI	%	30.5	-15.5	-10.5	-7.0
Winter wheat					
Yield	(t/ha)	11.291	+2.309	+2.400	+2.755
WP_{ET}	(kg/m^3)	2.46	+1.01	+1.10	+1.57
LGP	(d)	251	-30	-22	-15
WSI	%	0.0	0.0	0.0	0.0
CSI	%	33.0	-11.0	-8.0	-5.0
Potato					
Yield	(t/ha)	11.388	-0.830	+1.375	+2.826
WP_{ET}	(kg/m^3)	3.35	+0.28	+0.91	+1.24
LGP	(d)	116	-19	-11	-7
WSI	%	16.6	-1.5	+3.6	+15.7
CSI	%	0.0	0.0	0.0	0.0
Sugar beet					
Yield	(t/ha)	14.061	-1.668	+0.948	+1.980
WP_{ET}	(kg/m^3)	3.16	+0.02	+0.43	+0.75
LGP	(d)	168	-38	-25	-17
WSI	%	3.1	-1.0	1.5	12.1
CSI	%	6.5	-3.5	-3.5	-2.5
Peas					
Yield	(t/ha)	2.096	+0.264	+0.456	+0.558
WP_{ET}	(kg/m^3)	1.09	+0.30	+0.37	+0.41
LGP	(d)	73	-7	-6	-4
WSI	%	15.4	-1.3	-0.1	5.1
CSI	%	14.0	-6.0	-4.0	-3.0

Table B.5: Changes in seasonal crop yield, crop water productivity (WP_{ET}), length of the growing period (LGP), water stress index (WSI) and cold stress index (CSI) in 2050 under adapted management as compared to historical conditions (1985-2014) for the Plankbeek catchment (n=30). Presented ranges for future conditions represent the variety between the median values of the 7 GCMs. A positive change value represents an increase, while a negative value represents a decrease.

		Historical median	**Future median change under adapted management**		
			minimum	**median**	**maximum**
Maize					
Yield	(t/ha)	10.19	+0.563	+1.567	+1.982
WP_{ET}	(kg/m^3)	2.64	+0.35	+0.62	+0.64
LGP	(d)	133	-22	-8	+1
WSI	%	4.1	-1.9	-1.1	+2.7
CSI	%	30.5	-15.1	-9.5	-6.5
Winter wheat					
Yield	(t/ha)	11.291	+2.911	+3.069	+3.428
WP_{ET}	(kg/m^3)	2.46	+0.98	+1.12	+1.55
LGP	(d)	251	-24	-16	-10
WSI	%	0.0	0.0	0.0	0.0
CSI	%	33.0	-11.0	-8.0	-6.0
Potato					
Yield	(t/ha)	11.388	-0.180	+1.920	+3.638
WP_{ET}	(kg/m^3)	3.35	+0.38	+0.96	+1.23
LGP	(d)	116	-15	-7	-4
WSI	%	16.6	-4.0	+2.6	+14.2
CSI	%	0.0	0.0	0.0	0.0
Sugar beet					
Yield	(t/ha)	14.061	-0.469	+2.906	+4.030
WP_{ET}	(kg/m^3)	3.16	+0.21	+0.72	+1.07
LGP	(d)	168	-23	-9	+0
WSI	%	3.1	-1.0	+2.7	+12.7
CSI	%	6.5	-2.5	-1.5	+0.0
Peas					
Yield	(t/ha)	2.096	+0.564	+0.747	+0.833
WP_{ET}	(kg/m^3)	1.09	+0.42	+0.50	+0.55
LGP	(d)	73	-3	+0	+3
WSI	%	15.4	-3.7	-2.8	+1.7
CSI	%	14.0	-4.0	-3.0	-2.0

Table B.6: Changes in median annual discharge in 2050 as compared to historical conditions (1985-2014) for the Plankbeek catchment under traditional and adapted management (n=30). Presented ranges (minimum, median and maximum) for future conditions represent the variety between the median values of the 7 GCMs. A positive change value represents an increase, while a negative value represents a decrease of flow.

	Historical median (mm/year)	**Future median change (%)**		
		minimum	**median**	**maximum**
Traditional management				
Annual total discharge	277	+11	+31	+77
Annual baseflow	157	-1	+10	+44
Annual interflow	43	-3	+3	+12
Annual overland flow	77	+6	+10	+20
Adapted management				
Annual total discharge	277	+10	+28	+75
Annual baseflow	157	+11	+23	+59
Annual interflow	43	0	+5	+14
Annual overland flow	77	-9	-6	+2

Appendix C

SWAT comparison

Table C.1: Crops for which AquaCrop and SWAT parameter sets are published in literature (*) or included in the software database (**). Source: Van Gaelen (2016a), Shrestha et al. (2016), and Arnold et al. (2012).

Crop	**AquaCrop**	**SWAT**
Alfalfa	*	**
Amaranthus	*	
Apple		**
Asparagus		**
Bambara Groundnut	*	
Beans	*	**
Bermudagrass		**
Bluestem		**
Brocolli		**
Bromegrass		**
Cabbage	*	**
Canola	*	**
Carrot		**
Cauliflower		**
Celery		**
Clover		**
Cotton	**	**
Cowpeas		**
Cucumber		**
Eastern Gammagrass		**
Eggplant	*	**
Faba Bean	*	
Flax		**
Honey mesquite		**
Indiangrass		**
Johnsongrass		**
Kentucky bluegrass		**
Lentils		**
Lettuce		**
Maize	**	**
Melon		**
Millet	*	**
Miscanthus grass	*	
Oak		**

Table C.1 Cont.: Crops for which AquaCrop and SWAT parameter sets are published in literature (*) or included in the software database (**). The SWAT database might contain multiple parameter sets for the same crop to distinguish different crop varieties (not listed here). Source: Van Gaelen (2016a), Shrestha et al. (2016), and Arnold et al. (2012).

Crop	**AquaCrop**	**SWAT**
Oats	*	**
Onion	*	**
Peanut		**
Peas	*	**
Pepper	*	**
Pine		**
Poplar		**
Potato	**	**
Quinoa	**	
Rice	**	**
Rye		**
Ryegrass		**
Sesbania		**
Sideoats grama		**
Sorghum	**	**
Soybean	**	**
Spinach		**
Spring barley	**	**
Spring wheat	**	**
Strawberry		**
Sugar beet	**	**
Sugarcane	**	**
Sunflower	**	**
Sweet Potato	*	**
Switchgrass		**
Tall fescue grass		**
Taro	*	
Tea	*	
Tef	**	
Timothy grass		**
Tobacco		**
Tomato	**	**
Vetch	*	
Wheatgrass		**
Wildrye		**
Winter wheat	*	**

Table C.2: Required SWAT crop parameters to simulate crop growth, transpiration and production under non-limiting conditions (nl), as well as conditions with elevated CO_2 concentrations, water (w), temperature (t) and soil fertility (f) stress. Presented parameters are specified in crop.dat or .mgt files. Source: Neitsch et al. (2011) and Arnold et al. (2012).

Parameter	Description	Units	Conditions
Canopy development			
ALAI _MIN[2,3]	Minimum leaf area index for plant during dormant period	m^2/m^2	nl
BLAI	Maximum potential leaf area index	m^2/m^2	nl
CHTMX	Maximum canopy height	m	nl
DLAI	Fraction of growing season when senescence becomes dominating growth process	-	nl
FRGRW1	Fraction of growing season corresponding to 1st point on optimal leaf area development curve	-	nl
FRGRW2	Fraction of growing season corresponding to 2nd point on optimal leaf area development curve	-	nl
LAIMX1	Fraction of maximum leaf area index corresponding to 1st point on optimal leaf area development curve	-	nl
LAIMX2	Fraction of maximum leaf area index corresponding to 2nd point on optimal leaf area development curve	-	nl
PHU	Total heat units required for plant to reach maturity	heat units	nl
T _BASE	Minimum temperature for plant growth	°C	t
T _OPT	Optimal temperature for plant growth	°C	t
Transpiration			
FRGMAX[1]	Fraction of maximum leaf stomatal conductance corresponding to second point on the stomatal conductance curve	-	nl
GSI[1]	Maximum stomatal conductance at high solar radiation and low vapour pressure deficit	m/s	nl
VPDFR[1]	Vapour pressure deficit corresponding to second point on the stomatal conductance curve	kPa	nl

Table C.2 Cont.: Required SWAT crop parameters to simulate crop growth, transpiration and production under non-limiting conditions (nl), as well as conditions with elevated CO_2 concentrations, water (w), temperature (t) and soil fertility (f) stress. Presented parameters are specified in crop.dat or .mgt files. Source: Neitsch et al. (2011) and Arnold et al. (2012).

Parameter	**Description**	**Units**	**Conditions**
Biomass production			
BIO_E	Radiation use efficiency in ambient CO_2	kg MJ/ha m^2	nl
BIO_LEAF[3]	Fraction of tree biomass accumulated each year that is converted to residue during dormancy	-	nl
BMDIEOFF	Biomass die-off fraction at dormancy	-	nl
BMX_TREES[3]	Maximum biomass for a forest	t/ha	nl
EXT_COEF	Light extinction coefficient	-	nl
MAT_YRS[3]	Number of years required for tree species to reach full development	y	nl
RSR1C	Root to shoot ration at the beginning of the growing season	-	nl
RSR2C	Root to shoot ration at the end of the growing season	-	nl
WAVP	Rate of decline in radiation use efficiency per unit increase in vapor pressure deficit	kg MJ/ha m^2 kPa	nl
BIOEHI	Radiation use efficiency at elevated CO_2 atmospheric concentration value for CO2HI	kg MJ/ha m^2	co
CO2HI	Elevated CO_2 atmospheric concentration corresponding to 2nd point on the radiation use efficiency curve	ppmv	co
PLTNFR(1)	Normal fraction of nitrogen in plant biomass at emergence	-	f
PLTNFR(2)	Normal fraction of nitrogen in plant biomass at 50% maturity	-	f
PLTNFR(3)	Normal fraction of nitrogen in plant biomass at maturity	-	f
PLTPFR(1)	Normal fraction of nitrogen in plant biomass at emergence	-	f
PLTPFR(2)	Normal fraction of nitrogen in plant biomass at 50% maturity	-	f
PLTPFR(3)	Normal fraction of nitrogen in plant biomass at maturity	-	f
Yield			
CNYLD	Fraction of nitrogen in yield	-	f
CPYLD	Fraction of phosphorus in yield	-	f
HVSTI	Potential harvest index at maturity for optimal growing conditions	-	nl
WSYF	Lower limit of harvest index for plant in drought conditions	-	w

Table C.2 Cont.: Required SWAT crop parameters to simulate crop growth, transpiration and production under non-limiting conditions (nl), as well as conditions with elevated CO_2 concentrations, water (w), temperature (t) and soil fertility (f) stress. Presented parameters are specified in crop.dat or .mgt files. Source: Neitsch et al. (2011) and Arnold et al. (2012).

Parameter	Description	Units	Conditions
Root distribution			
RDMX	Maximum root depth	mm	nl
EPCO	Plant uptake compensation factor	-	nl
P_UPDIS	Phosphorus uptake distribution parameter	-	f
N_UPDIS	Nitrogen uptake distribution parameter	-	f

[1] Only required if transpiration is modelled using Penman-Monteith method
[2] Only required for crops that are perennials
[3] Only required for crops that are trees

Table C.3: SWAT and AquaCrop soil physical parameters required to simulate the soil water balance. Soil parameter are specified in the models' .sol files. Surface runoff parameters marked with * are also affected by management parameters specified in the .mgt (SWAT) or .MAN (AquaCrop) file. Source: Raes et al. (2015), Neitsch et al. (2011), and Arnold et al. (2012).

SWAT			AquaCrop		
Parameter	**Description**	**Units**	**Parameter**	**Description**	**Units**
Per soil layer					
SOL_Z	Depth from soil surface to bottom of layer	mm	Th	Thickness of the soil layer	m
SOL_K	Saturated hydraulic conductivity	mm/h	K_{sat}	Saturated hydraulic conductivity	mm/d
SOL_AWC	Available water capacity of soil layer	mm/mm	θ_{SAT}	Soil water content at saturation	vol%
SOL_CLAY	Clay content	wgt%	θ_{FC}	Soil water content at field capacity	vol%
SOL_SILT	Silt content	wgt%	θ_{PWP}	Soil water content at permanent wilting point	vol%
SOL_SAND	Sand content	wgt%			
SOL_BD	Moist bulk density	g/cm^3			
Per land unit					
SOL_ZMX	Maximum rooting depth in soil profile	mm	Res	Depth of restrictive layer	m
CN2*	Curve number for moisture condition II	-	CN	Curve number for moisture condition II for bare topsoil	-
CNOP*	Curve number for moisture condition II specified in plant, harvest or tillage operation	-	$f_{CN,mgmt}$*	Curve number adjustment factor for field surface management	-
SOL_ALB	Moist soil albedo of top layer	-	REW	Readily evaporable water from top layer	mm
			CRa	Capillary rise parameter a	-
			CRb	Capillary rise parameter b	-

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Curriculum vitae

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Professional experience

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2013-2016	PhD representative in the board of the Department of Earth and Environmental Sciences and the Bachelor programme committee of the Faculty of Bioscience Engineering, KU Leuven (Belgium)

Publications

Articles published in international, peer-reviewed academic journals

Van Gaelen, H, Delbecque, N, Abrha, B, Tsegay, A, and Raes, D (2016a). Simulation of crop production in weed-infested fields for data-scarce regions. *The Journal of Agricultural Science*, 154 (6), 1026–1039. DOI: http://dx.doi.org/10.1017/S0021859615000982

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